

ADAPTIVE FREQUENCY HOPPED ALAMOUTI-CODED OFDM SYSTEM

A Thesis Submitted

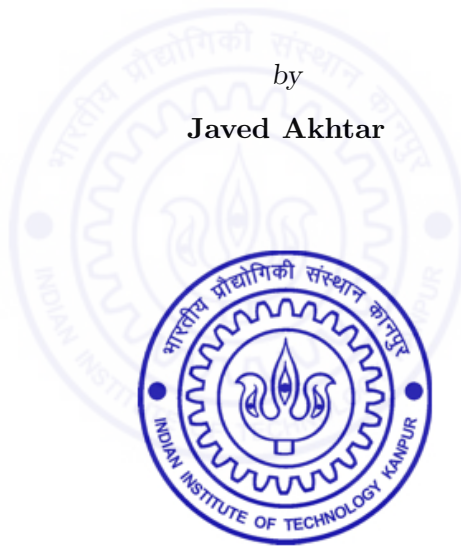
in Partial Fulfillment of the Requirements

for the Degree of

Master of Technology

by

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to the

DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY, KANPUR

June 2013



CERTIFICATE

It is certified that the work contained in the thesis entitled "*Adaptive Frequency Hopped Alamouti-Coded OFDM System*" by *Javed Akhtar* has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

June 2013

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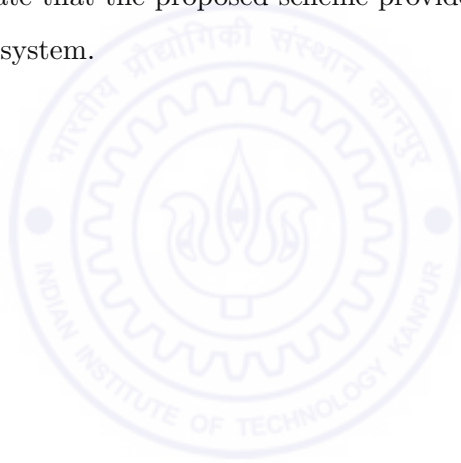
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Abstract

In modern wireless communication, power and bandwidth are two of the most important constraints for a system that has to be taken into account. Recent demands for high data rate and high capacity has set an urge for systems that can support large chunks of data and large number of users. For a power and bandwidth limited system, enhancing the system performance provides a good solution to meet these demands. In this thesis we consider OFDM and Alamouti-Coded OFDM systems with an objective of improving the system performance using adaptive hopping. In this context we propose an AFH (Adaptive Frequency Hopped) system that improves the performance of the system. We use Alamouti-Coded OFDM system that has the advantage of transmit diversity as well as high data rate. Simulation results demonstrate that the proposed scheme provides high gain and hence enhances the performance of the system.



to my parents



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First and foremost I would like to thank my thesis guide *Dr. Govind Sharma*. This work would not be possible without his constant guidance and regular help. Next, I would like to thank all the professors in IIT Kanpur, who introduced me to many interesting topics of Communication and Signal Processing and inculcated interest in this field. I would also like to thank all my classmates, friends and lab mates for their support whenever it was needed.



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List of Abbreviations

AFH	Adaptive Frequency Hopped
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
CSI	Channel State Information
DFT	Discrete Fourier Transform
FFT	Fast-Fourier Transform
FH	Frequency Hopping
ICI	Inter-Carrier Interference
IDFT	Inverse Discrete Fourier Transform
IFFT	Inverse Fast Fourier Transform
ISI	Inter symbol Interference
LQA	Link Quality Analysis
LS	Least Square
MB-OFDM	Multi-Band OFDM
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output

MMSE	Minimum Mean Square Estimation
MRRC	Maximal-Ratio Receiver Combining
OFDM	Orthogonal Frequency Division Multiplexing
SNR	Signal to Noise Ratio
STBC	Space Time Block Code
UWB	Ultra-Wideband



Chapter 1

Introduction

OFDM (Orthogonal Frequency Division Multiplexing) [1], [2] for its significant advantages has emerged as a ubiquitous technology for broadband wireless networks compared to other multi-carrier modulations. In OFDM a wideband channel is decomposed into several parallel narrowband frequency flat wireless fading channels thus avoiding the problem of inter-symbol interference in frequency selective channels. OFDM can be implemented using IFFT (Inverse Fast Fourier Transform), therefore the complexity of implementation of OFDM is less and increases slightly faster than linear with data rate or bandwidth. Further, OFDM can also exploit frequency diversity in a channel. Fig.1.1 shows the proposed scheme for adaptive frequency hopping using Alamouti coded OFDM. In this scheme the OFDM scheme is used using two transmit antenna and one receive antenna. The transmission uses Alamouti coding scheme in which two OFDM symbols are transmitted over two OFDM time period. Before OFDM modulation the adaptive hopping is done based on the channel condition as received from the receiver through the feedback channel. The adaptive hopping allows the system to select the best of the channels for transmission and also avoids those channels which have low SNR (Signal to Noise Ratio) and thus it improves the performance of the system.

The channel estimate is performed on the pilot symbols that are transmitted and that are known at the receiver. The estimated channel condition is informed to the transmitter through a feedback channel. The transmitter decides the best of the channels out of all available channels for transmission and the receiver performs de-hopping of the symbols before mapping it on the constellation.

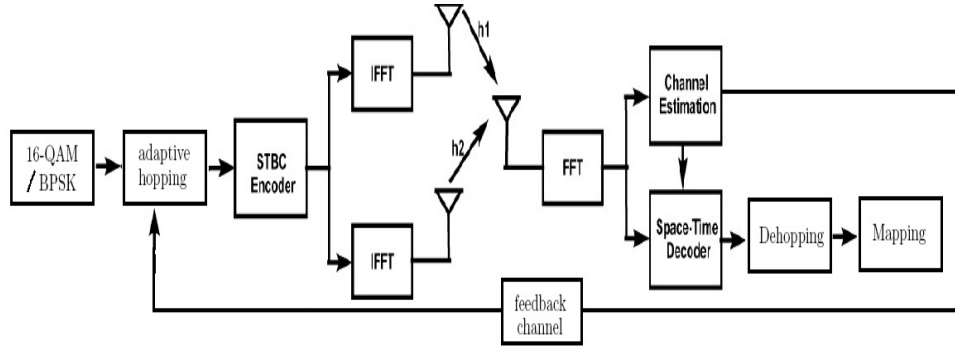


Figure 1.1: Adaptive Frequency Hopping Space Time Block Code OFDM

1.1 Diversity

Diversity order measures the number of available independent copies of the same signal. The performance gain arises from the fact that it is unlikely that all the independent samples of the fading process are in a deep fade. If all the channels were perfectly correlated and if one of the channels were in deep fade, then all the channels would be in a deep fade i.e, there will be no diversity at all. The diversity gain is achieved using one of the following diversity scheme:

- 1) Frequency Diversity: Same signal is transmitted on more than one carrier frequencies at the same time to have same sample of signal at the receiver.
- 2) Time Diversity: Same signal is transmitted over different time instants to receive multiple copies of same signal.
- 3) Space Diversity: Receiver or Transmitter has multiple antennas spaced apart to transmit the same signal or multiple signal at the same time.

1.2 Motivation

Several works have been reported on the performance analysis of OFDM and on MIMO-OFDM systems. The high bit rate achieved by OFDM system gives it an advantage but incorporating MIMO (Multiple Input Multiple Output) antenna system provides spatial diversity or multiplexing gains and also addresses to the ever-increasing demand for capacity [3], but putting multiple antennas at the mobile-station will make it costly. Hence, we look

for an alternate system so that the system performs better. Here, we propose a system of Alamouti coded OFDM which provides diversity gain and also try to improve the system performance by using adaptive hopping. In this context, we provide a system that achieves better performance as well as avoids bad channels by selecting best of available channels before transmission of data. Simulation results demonstrate that the scheme achieves better performance as compared to existing Alamouti and OFDM schemes.

1.3 Thesis Contribution

In this thesis we were able to model a system that can perform better than the existing OFDM [4] and STBC (Space Time Block Code) systems. Since, we used both OFDM and STBC along with adaptive hopping in our system. Hence, we were able to achieve the advantages of high transmission rate through OFDM scheme and that of transmit diversity gain through Alamouti coding scheme. The use of adaptive hopping helps the system to transmit through best of channels and thus to perform better than OFDM, STBC-OFDM and AFH-OFDM systems.

1.4 Organization

The thesis is organised as follows. In *chapter 2* the basic concepts of OFDM is explained and the frequency domain analysis is also done. In *chapter 3* we discuss the different hopping schemes for OFDM data. In *chapter 4* we discuss the different channel estimation schemes and also different types of pilot arrangement schemes. In *chapter 5* the concept of STBC is discussed along with Alamouti coding scheme and Alamouti coded OFDM.

Chapter 2

Orthogonal Frequency Division Multiplexing

2.1 Introduction

OFDM is a type of multichannel transmission scheme through which very high data transmission rate can be achieved. The transmitting sub-carriers used are orthogonal to each other. This type of transmission scheme is bandwidth efficient as the multiple sub-carrier's spectra overlap without causing interference. The modulation at the transmitter uses IDFT (Inverse Discrete Fourier Transform) and DFT (Discrete Fourier Transform) at the receiver. Although IDFT and DFT can be implemented using IFFT and FFT (Fast-Fourier Transform), which are complexity efficient i.e, their processing algorithm is much faster. One of the advantage of OFDM is that it mitigates the effect of ISI (Inter symbol Interference) between OFDM symbols through addition of cyclic prefix whose length is taken as equal to or greater than the channel delay. OFDM divides a frequency-selective channel into N number of flat fading channels which solves the issue of signal distortion. The N sub-carriers are generated using IDFT/DFT. OFDM implementation using IDFT/DFT is shown in figure (2.1) [5].

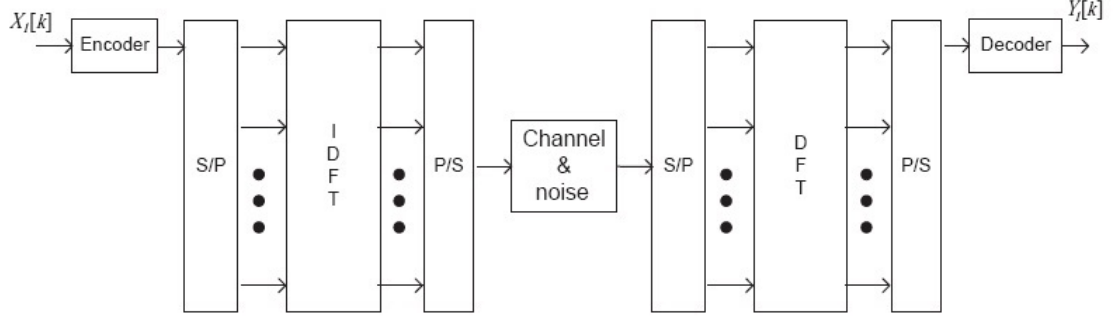


Figure 2.1: OFDM transmission scheme implemented using IDFT/DFT

2.2 Basic Principle of OFDM

2.2.1 Orthogonality

For an OFDM signal the different sub-carriers can be represented as $\{e^{j2\pi f_k t}\}_{k=0}^{N-1}$ at $f_k = \frac{k}{T_{sym}}$, where $0 \leq t \leq T_{sym}$. In discrete domain it can be shown that the orthogonality condition is satisfied if [5]:

$$\begin{aligned}
 \frac{1}{N} \sum_{n=0}^{N-1} e^{j2\pi \frac{k}{T_{sym}} n T_s} \cdot e^{-j2\pi \frac{i}{T} n T_s} &= \frac{1}{N} \sum_{n=0}^{N-1} e^{j2\pi \frac{k}{T_{sym}} \frac{nT}{N}} e^{-j2\pi \frac{i}{T_{sym}} \frac{nT_{sym}}{N}} \\
 &= \frac{1}{N} \sum_{n=0}^{N-1} e^{j2\pi \frac{(k-i)}{N} n} \\
 &= \begin{cases} 1, & \forall \text{ integer}, k = i \\ 0, & \text{otherwise} \end{cases} \quad (2.1)
 \end{aligned}$$

Where, $T_s = \frac{T_{sym}}{N}$. The sub-carriers of OFDM signal must satisfy the above equation.

2.2.2 OFDM Modulation and Demodulation

The discrete-time baseband model of an OFDM signal can be represented by equation below [1]

$$y[m] = \sum_{l=0}^{L-1} h_l x[m-l] + w[m] \quad (2.2)$$

Where, L is the number of taps of the Rayleigh channel model, w is the AWGN (Additive White Gaussian Noise) and h_l is the l_{th} tap of the Rayleigh channel. The channel h is

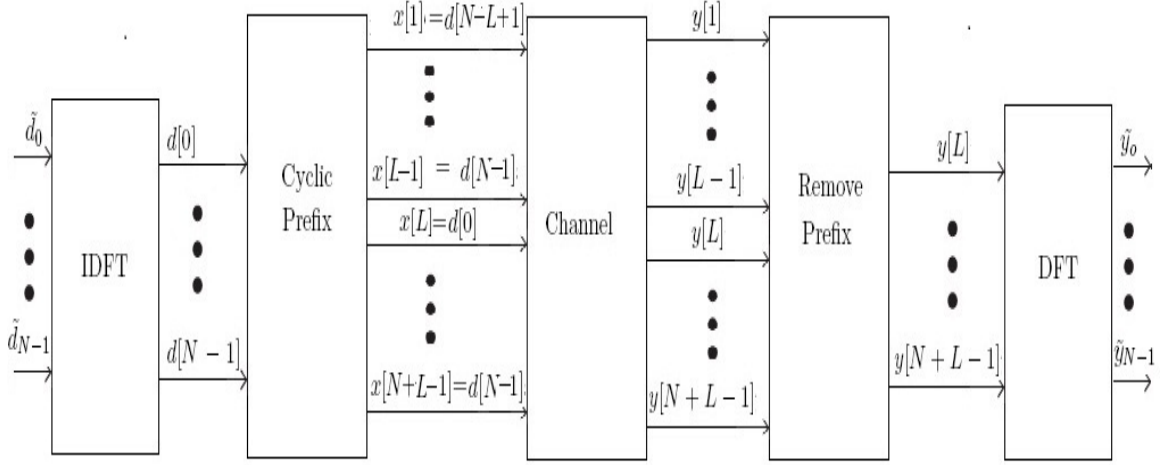


Figure 2.2: OFDM transmission and reception scheme

normally distributed ($h \sim N(0, 1)$). Fig.2.2 shows the complete OFDM system model for transmission of data blocks as given in [1]. The vector $[\tilde{d}_0, \tilde{d}_1, \dots, \tilde{d}_{N-1}]^T$ represents the data prior to IDFT, where N denotes the block length of an OFDM symbol. The data vector after the IDFT can be represented as [1]

$$[d[0], d[1], \dots, d[N-1]]^T$$

To mitigate the effects of ISI, cyclic prefix of length $L-1$ is added to the symbols. The cyclic prefix consists of the data symbols rotated cyclically as shown in Fig.2.3 [1]. Thus, the length of data block becomes $N+L-1$ prior to transmission.

$$x = [d[N-L+1], d[N-L+2], \dots, d[N-1], d[0], d[1], \dots, d[N-1]]^T \quad (2.3)$$

Thus, the output of channel can be written as:

$$y[m] = \sum_{l=0}^{L-1} h_l x[m-l] + w[m], \quad m = 1, 2, \dots, N+L-1$$

The receiver ignores the first $L-1$ received values as it accounts for ISI and considers values present in the interval $m \in [L, N+L-1]$ and the output within this interval is

$$y[m] = \sum_{l=0}^{L-1} h_l d[(m-L-l) \text{ modulo } N] + w[m] \quad (2.4)$$

The output can be denoted as

$$y = [y[L], \dots, y[N + L - 1]]^T$$

Also, the L tap multipath channel can be written as a vector of length N

$$h = [h_0, h_1, \dots, h_{L-1}, 0, \dots, 0]^T \quad (2.5)$$

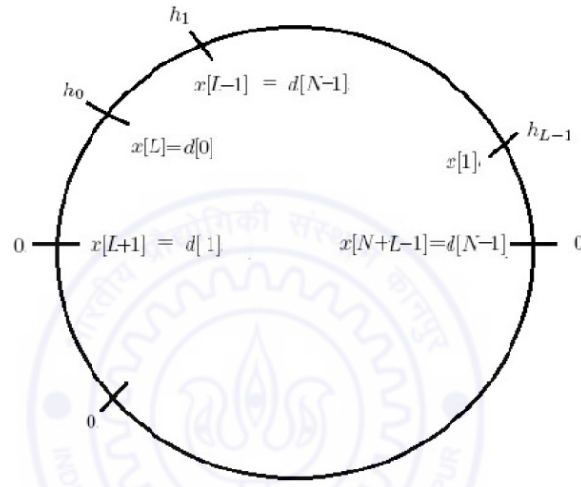


Figure 2.3: Convolution between Channel (h) and data symbols (d)

Fig.2.3 shows the convolution between the input x and the channel h . The output of the channel is decided by multiplying corresponding values of data and channel values on the circle. Output at different times can be obtained by rotating the x values with respect to h values [1]. Thus the output in terms of convolution can be shown as

$$y = h \otimes d + w \quad (2.6)$$

Here, $\otimes$ represents the cyclic convolution. After the removal of cyclic prefix the receiver performs the DFT on the vector y to obtain $\tilde{y} = [\tilde{y}_0, \tilde{y}_2, \dots, \tilde{y}_{N-1}]$.

2.3 OFDM Block Structure

Fig.2.4 shows the structure of the OFDM block along with the cyclic prefix. Here, T_G represents the guard interval duration which is equal to length of cyclic prefix to counter the

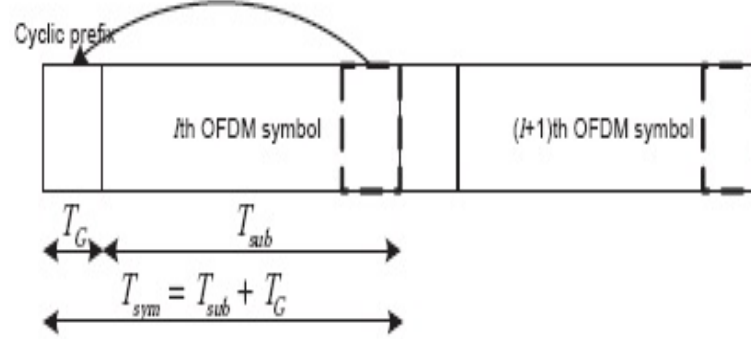


Figure 2.4: OFDM Block Structure

effects of ISI. T_{sub} represents the data interval and T_{sym} represents the total symbol duration i.e.,

$$T_{sym} = T_{sub} + T_G$$

The arrow in the figure for cyclic prefix shows that the data symbols of length $L - 1$ from the end is appended at the beginning of the block. OFDM converts a wideband channel into multiple parallel narrowband sub-channels. The advantage of addition of cyclic prefix is that it mitigates the effects of ISI whereas it's addition increases the overhead which amounts for a loss of $\frac{L}{N_c + L}$ of total transmission time and also accounts for the same fraction of power loss of total power available at the transmitter for the transmission of the overhead. The length of the cyclic prefix depends on the maximum delay of the channel. If the coherence time is more than the channel delay then the channel is said to be underspread channel or slow varying channel and hence the overhead needed will be less as compared to a fast varying channel.

2.4 Frequency Domain Analysis of OFDM

Fig.2.5 shows the frequency domain representation of OFDM system model. The data vector in frequency domain is represented by $X = [X[0], X[1], \dots, X[N - 1]]^T$. The channel is represented as $H = [H[0], H[1], \dots, H[N - 1]]^T$ and the output of the channel is represented as $Y = [Y[0], Y[1], \dots, Y[N - 1]]^T$. Fig.2.5 shows that the channel in frequency domain can

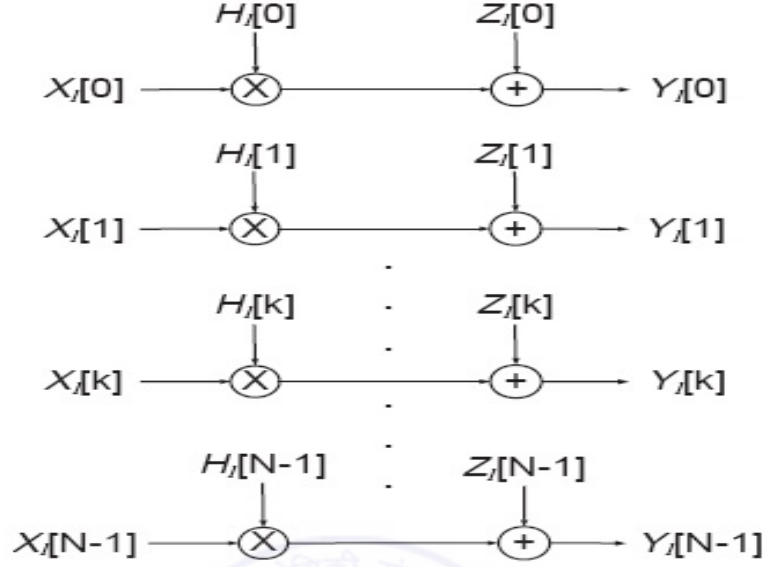


Figure 2.5: Frequency Domain equivalent model of OFDM

be modelled into independent parallel sub-channels. The number of sub-channels depends on the number of narrowband channels obtained by dividing the available bandwidth. Let, W denote the bandwidth available and B represents the sub-carrier spacing, then the number of sub-channels is given by:

$$N = \frac{W}{B}$$

The sub-carrier spacing B is so chosen so that it is less than the coherence bandwidth i.e, the effects of channel is linear. Hence, the sub-carrier spacing should follow the below inequality for distortionless transmission :

$$B \leq B_c$$

Where, B_c represents coherence bandwidth i.e, the frequency band in which the performance of channel is invariant. The transmission of data in frequency domain can be analyzed as parallel stream across the channel since, the ICI is zero as the sub-carriers are orthogonal to each other. Hence, the system model can be written mathematically as

$$Y[k] = X[k]H[k] + Z[k]; \quad k = 0, 1, \dots, N-1 \quad (2.7)$$

Where, $X[k]$, $H[k]$ and $Y[k]$ represents the data, channel and output across the k th frequency sub-carrier. Hence, the data can be detected at the receiver using a one tap equalization, i.e,

by simply dividing the received symbol by the channel

$$\hat{X}[k] = \frac{Y[k]}{H[k]} \quad k = 0, 1, \dots, N - 1$$

Where, $\hat{X}[k]$ is the estimated symbol. The above estimation is possible only if the complete channel state information is assumed to be known at the receiver. Practically, to detect the symbol one has to apply channel estimation at the receiver. Channel estimation techniques for OFDM symbols are discussed in more details in chapter 4.



Chapter 3

Frequency Hopping in OFDM System

3.1 Introduction

Frequency Hopping (FH) is one of the spread spectrum techniques. OFDM technology, as known, is used for high bit-rate transmission as it converts a frequency-selective channel into ' N ' number of parallel flat fading channels. The performance of OFDM, however may suffer from absence of diversity in frequency selective channels. Thus, to exploit the frequency diversity and also for low probability of interception, FH-OFDM systems has been developed. The frequency hopping pattern across the available tones is generated by a pseudorandom pattern. Hence, the user using frequency hopping does not transmit on the same tone in every symbol interval, instead uses hopping pattern to move to different tone in each symbol interval. For more information one can study [6]. There are two types of systems that use frequency hopping for OFDM. In one of type the RF carrier frequency is hopped [7], and it has been used in one of the UWB (Ultra-Wideband) standard called MB-OFDM (Multi-Band OFDM) and in the other sub-carriers are hopped.

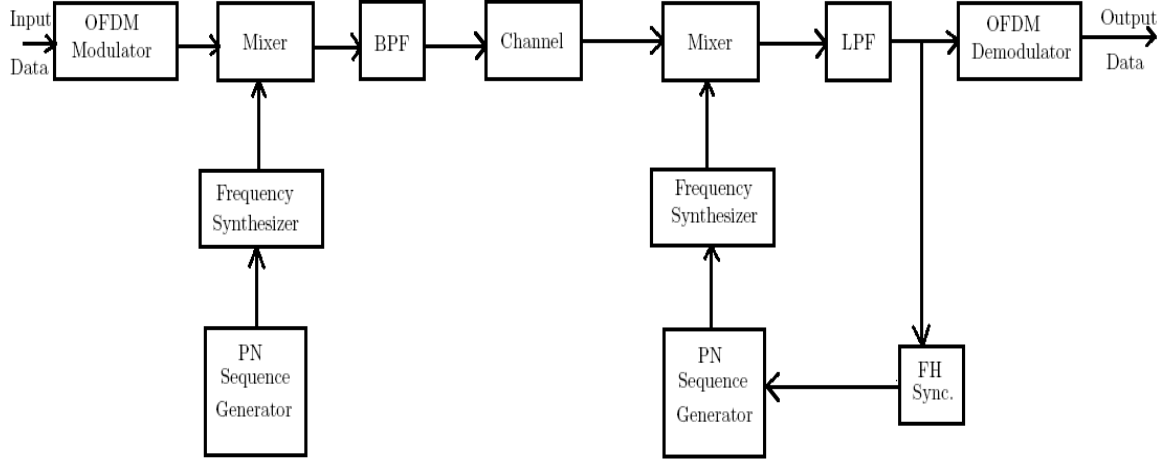


Figure 3.1: Block Diagram of RF-FH-OFDM System

3.2 RF-FH-OFDM

Fig.3.1 represents the RF-FH-OFDM system. In this technique before transmission through RF antenna, the signal is mixed with frequency synthesizer. The PN sequence generator generates random sequence at the transmitter which is used by frequency synthesizer to generate frequency within the bandwidth available. Then the mixer part mixes the generated frequency with the signal obtained after OFDM modulation. The receiver similarly generates random sequence using PN sequence generator. The sequence generated at the receiver end is controlled using FH synchronizer, so that the sequence generated at the receiver matches the sequence generated at the transmitter. The FH synchronizer is very important block in the system because a mismatch in the sequence pattern may result into wrong detection of signal. Hence, to maintain proper synchronization between transmitter and receiver, the PN sequence generator at the two end of the system should be synchronized.

Let, $x_b[n]$ denote the baseband signal obtained after the OFDM modulation and w_i be the frequency generated by the frequency synthesizer. Both the informations are passed into the mixer part, whose output is denoted as $x_{rf}[n]$. Then the output of the mixer can be written as

$$x_{rf}[n] = x_b[n] * e^{jw_i n} \quad (3.1)$$

Fig.3.2 represents the signal model of the RF-FH-OFDM system. Figure (a) shows the

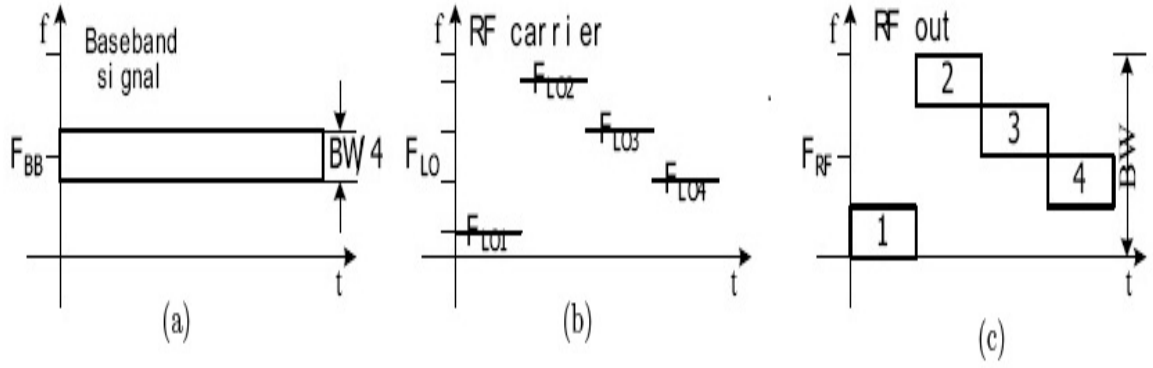


Figure 3.2: Representation of RF-FH-OFDM signal

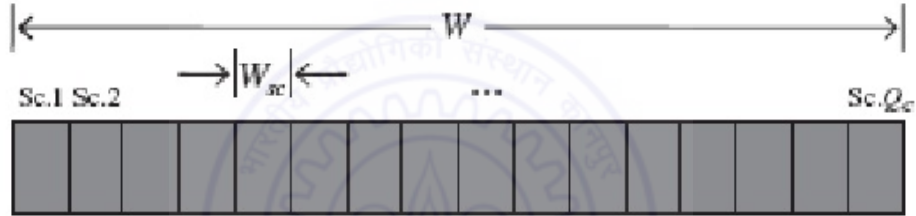


Figure 3.3: Conventional OFDM Sub-carrier Block structure

baseband model of the signal and figure (b) shows the RF carrier generated by the local oscillator in the frequency synthesizer at different time instants. Figure (c) shows the RF output of the mixer at different time instants.

3.3 Sub-carrier Hopping

Fig.3.3 shows the conventional block structure of OFDM, where W represents the bandwidth available for transmission, W_{sc} is sub-carrier bandwidth and Q_c is the total sub-carrier available. Where, Q_c is given by:

$$Q_c = \frac{W}{W_{sc}}$$

This pattern of transmission has each sub-carrier dedicated data index for each OFDM symbol. There are other two techniques [8] available where the sub-carriers are not dedicated to the data indices, instead are randomly allocated. They are

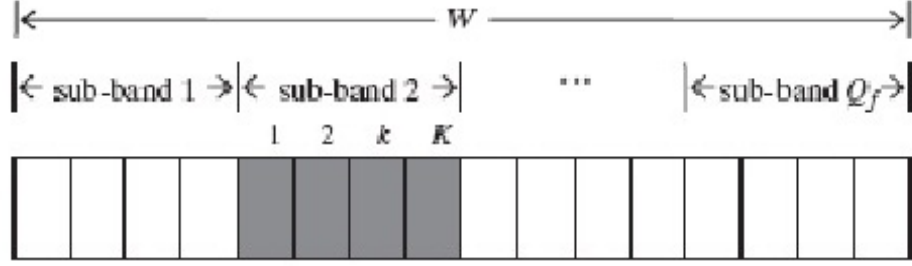


Figure 3.4: Uniform Sub-carrier Hopping

- (i) Uniform sub-carrier hopping and
- (ii) Non-Uniform sub-carrier hopping.

3.3.1 Uniform sub-carrier hopping

Fig.3.4 represents the uniform sub-carrier hopping technique. In this technique the sub-carriers are allocated randomly for each user.

Although the hopping for each user is uniform i.e, each sub-carrier occupied by the user is translated or hopped across the frequency by equal amount. In this technique the bandwidth W is partitioned into number of sub-bands as indexed in fig.3.4 from $q = 1, 2, \dots, Q_f$ and each of the sub-bands has K sub-carriers. Where,

$$Q_c = K.Q_f$$

and Q_c is the total number of sub-carriers [9]. Each sub-band is occupied by the user in a multi-user scenario. For a single user the same model can be implemented by selecting any K number of sub-carriers from the Q_c available sub-carriers. For every OFDM symbol, different translation along the W band is provided. The receiver has to be synchronized with the transmitter for estimating the hopping pattern for correct detection.

3.3.2 Non-uniform sub-carrier hopping

Fig.3.5 shows the non-uniform sub-carrier hopping technique. In this technique each sub-carrier of the user is randomly hopped across the W band available. For multi-user case the sub-carriers occupied are randomly distributed across the frequency band. One advantage of

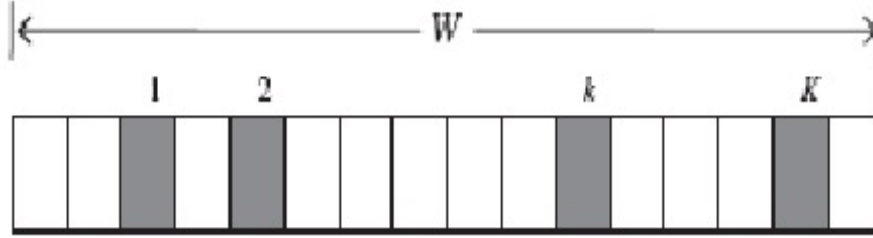


Figure 3.5: Non-uniform Sub-carrier Hopping

this hopping pattern is that it reduces the ICI (Inter-Carrier Interference). As in single user scenario the user can use any of the K sub-carriers from the Q_c available sub-carriers. The sub-carriers occupied by the user may not be adjacent to each other. As can be seen from fig.3.5 that the K sub-carriers are spread out across the frequency band. In this technique also a proper synchronization must exist between the transmitter and receiver for tracking the hopping pattern of the sub-carriers. The spacing between the sub-carriers of the same user might not be the same.

3.4 Adaptive Frequency Hopping

Fig.3.6 shows the adaptive frequency hopping OFDM system model. In this technique the frequency hopping is achieved through LQA (Link Quality Analysis) and based on channel condition [10]. At the receiver the LQA analyzes the channel quality based on received signal and communicates through feedback channel back to the transmitter. Hence, based on the channel condition the transmitter decides the hopping pattern for transmission. For some other adaptive based techniques one can refer [11].

Synchronization is easier in adaptive hopping because it is the receiver which analyzes the channel condition and feedbacks the link quality. Hence, the receiver is aware of the hopping pattern that will be adopted by the receiver for next OFDM symbols. The link quality analyzer checks the SNR and feedbacks the information back to the transmitter. This technique is different from the sub-carrier hopping as discussed in (3.2) in respect to hopping pattern, since, in sub-carrier hopping the hopping pattern was random but in adaptive hopping the

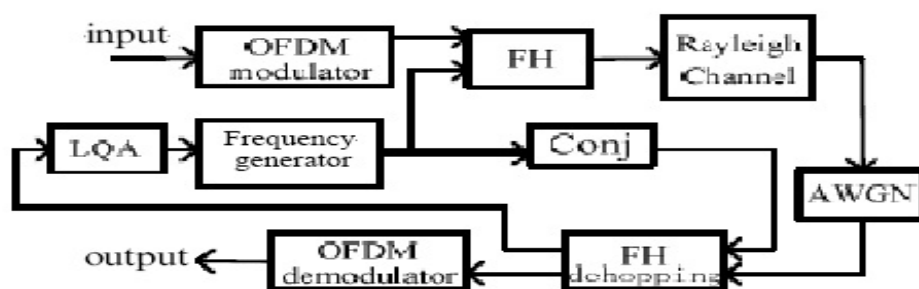


Figure 3.6: Adaptive Frequency Hopping Model

hopping pattern depends on channel condition.



Chapter 4

Channel Estimation Techniques

4.1 Introduction

The received OFDM symbols are generally distorted due to channel conditions and presence of noise. To efficiently recover the data, channel must be estimated and compensated. The channel can be estimated using pilot symbols [12] known at transmitter and receiver as well. Pilot-aided channel estimation for OFDM can be of three types based on pilot arrangements block type, comb type and lattice type.

4.2 Block Type

Block type pilot arrangement is shown in Fig.4.1. In block type, OFDM symbols with pilots at all sub-carriers are transmitted periodically for channel estimation. Using these pilots channel estimation is done. Let, S_t denote the period of pilot symbols. To mitigate the effects of time-varying channel, pilot symbols should be placed in respect to the coherence time. The pilot symbol period must satisfy the below inequality :

$$S_t \leq \frac{1}{f_D}$$

Where, f_D is the doppler frequency given by:

$$f_D = \frac{v}{c} * f_c * \cos \theta$$

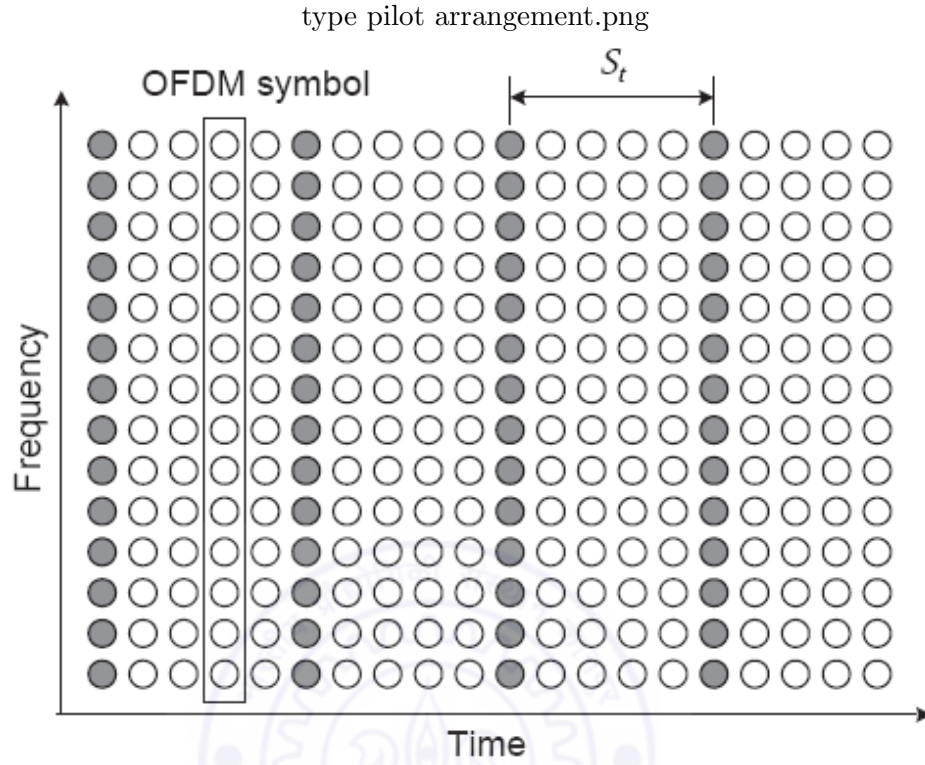


Figure 4.1: Block type pilot arrangement

Where, f_c is the carrier frequency, v is the speed of mobile station, c is the speed of light and θ is the angle of arrival of the signals.

Since pilot symbols are transmitted through all sub-carriers after a fixed period in time, this type of pilot arrangement will be suitable for slow-fading channels. But for fast-fading channels, this technique might add much of overhead to track the variation of channel as a result of reducing the period of pilot symbol transmission. Further, the channel estimation can be done using the LS (Least Square) estimation or using MMSE (Minimum Mean Square Estimation) method as will be described in 4.5.

4.3 Comb Type

Pilot arrangement for comb-type is shown in Figure 4.2. In comb-type, pilot tones are periodically located in each of the OFDM symbol, which are then used to interpolate and estimate data sub-channels in the frequency domain. Let pilot tones period in frequency be

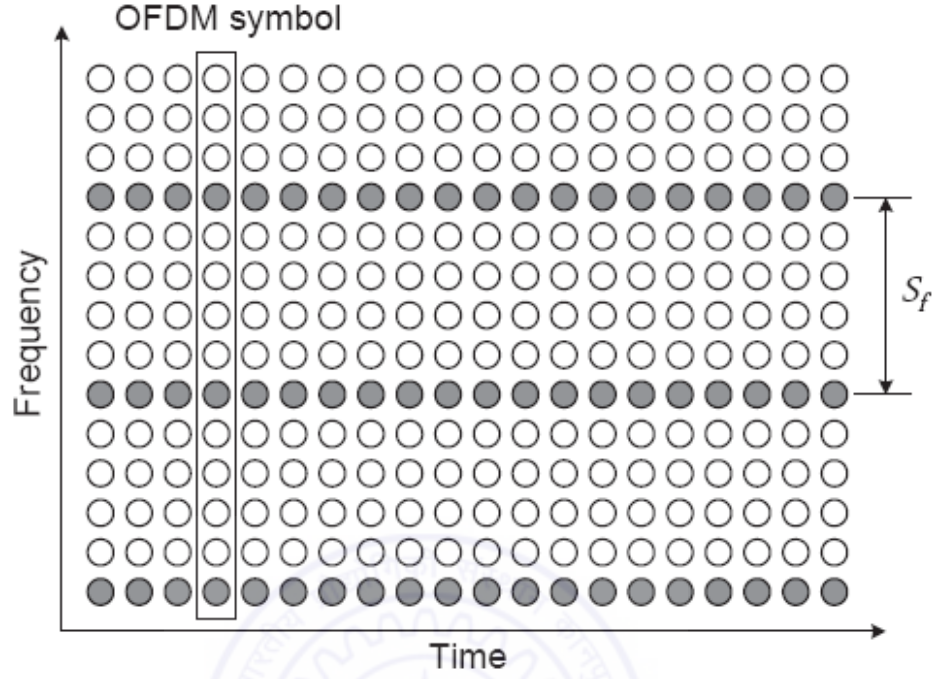


Figure 4.2: Comb type pilot arrangement

S_f . To mitigate the effects of frequency-selective channel, pilot symbols should be placed apart across the frequency band as the coherent bandwidth. The period for pilot symbols must satisfy the below inequality:

$$S_f \leq \frac{1}{\sigma_{max}}$$

Where σ_{max} is the maximum delay spread. For fast varying channel this type of pilot arrangement is more suitable as compared with the block-type pilot arrangement.

4.4 Lattice Type

Pilot arrangement for Lattice-type is shown in Figure 4.3. Pilot tones are placed periodically along the frequency and time axis. Pilot tones spaced in both frequency and time axis are used for interpolation and for channel estimation. Let, period for pilot symbols in frequency and time be S_f and S_t respectively. Hence, to mitigate the effects of frequency-variations and time-variation of channel, the arrangement of pilot symbols must satisfy the following

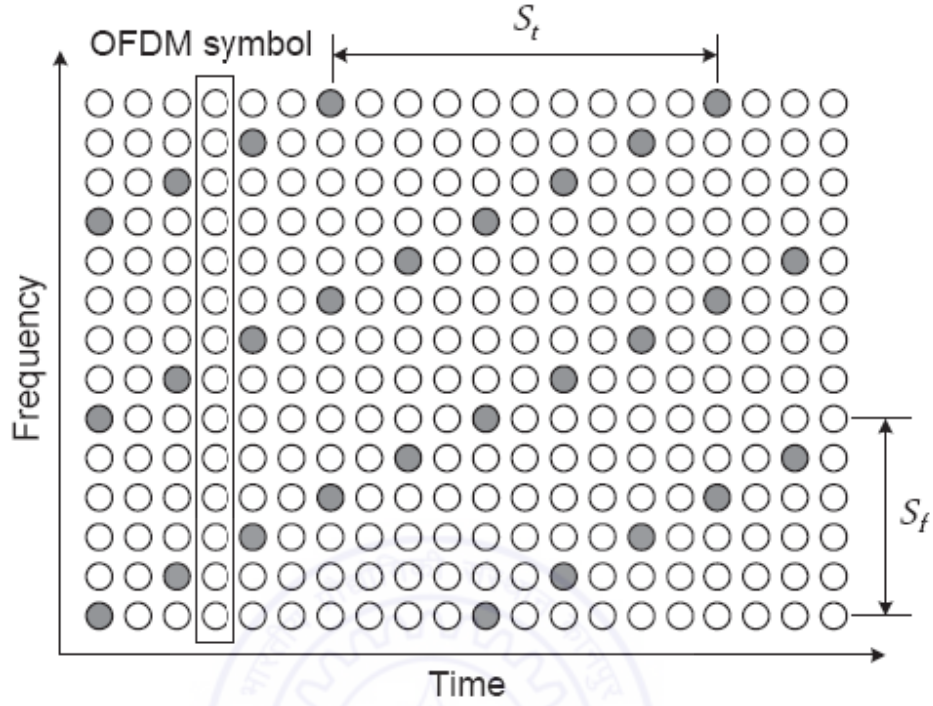


Figure 4.3: Lattice type pilot arrangement

equations:

$$S_f \leq \frac{1}{\sigma_{max}}$$

and

$$S_t \leq \frac{1}{f_D}$$

Where, σ_{max} is the maximum delay spread and f_D is the doppler frequency.

4.5 Training Symbol-Based Channel Estimation

Channel estimation based on training symbols provides good performance. The efficiency of transmission decreases because of the addition of overhead training symbols along with data symbols. Techniques used for channel estimation when pilot symbols are available are LS and MMSE. Each sub-carriers can be assumed to be orthogonal i.e, ICI-free. The diagonal

matrix for N sub-carriers for the training symbols can be represented as:

$$X = \begin{bmatrix} X[0] & 0 & \cdots & 0 \\ 0 & X[1] & \cdots & 0 \\ \vdots & & \ddots & 0 \\ 0 & \cdots & 0 & X[N-1] \end{bmatrix}$$

Where $X[K]$ represents the pilot tone present at the K th sub-carrier, with $E\{X[K]\} = 0$ and $Var\{X[K]\} = \sigma_x^2$, $K = 0, 1, \dots, N-1$. Note that X is given by a diagonal matrix, since we assume that all subcarriers are orthogonal. For each sub-carrier k , the received training signal can be represented as

$$Y \triangleq \begin{bmatrix} Y[0] \\ Y[1] \\ \vdots \\ Y[N-1] \end{bmatrix} = \begin{bmatrix} X[0] & 0 & \cdots & 0 \\ 0 & X[1] & \cdots & 0 \\ \vdots & & \ddots & 0 \\ 0 & \cdots & 0 & X[N-1] \end{bmatrix} \begin{bmatrix} H[0] \\ H[1] \\ \vdots \\ H[N-1] \end{bmatrix} + \begin{bmatrix} Z[0] \\ Z[1] \\ \vdots \\ Z[N-1] \end{bmatrix}$$

$$Y[k] = H[k]X[k] + z[k]$$

$$Y = HX + Z \quad (4.1)$$

H is the channel vector and Z is the noise vector, with $E\{Z[K]\} = 0$ and $Var\{Z[K]\} = \sigma_z^2$. Let channel estimate of H be denoted as $\hat{H}$.

4.5.1 LS Channel Estimation

The estimate of channel $\hat{H}$ is found using least-square estimation from below cost function so as to minimize the cost [5]

$$J(\hat{H}) = \|Y - X\hat{H}\|^2 \quad (4.2)$$

$$= (Y - X\hat{H})^H (Y - X\hat{H}) \quad (4.3)$$

$$= Y^H Y - Y^H X \hat{H} - \hat{H}^H X^H Y + \hat{H}^H X^H X \hat{H} \quad (4.4)$$

By taking the derivative of above function with respect to $\hat{H}$ and setting it to zero we get

$$X^H X \hat{H} = X^H Y$$

Hence, the LS estimate of channel is:

$$\hat{H}_{LS} = (X^H X)^{-1} X^H Y = X^{-1} Y$$

Assuming ICI-free condition for each sub-carrier, the LS estimate of channel can be written as

$$\hat{H}_{LS}[k] = \frac{Y[k]}{X[k]}, k = 0, 1, \dots, N-1 \quad (4.5)$$

4.5.2 MMSE Channel Estimation

Using the equation for LS solution $\hat{H}_{LS} = X^{-1} Y \triangleq \tilde{H}$. We define $\hat{H} \triangleq W \tilde{H}$, where W is the weight matrix and $\hat{H}$ is the MMSE estimate. The orthogonality principle states that estimated error $e = (H - \hat{H})$ will be orthogonal to $\tilde{H}$. Hence,

$$\begin{aligned} E\{e \tilde{H}^H\} &= E\{(H - \hat{H}) \tilde{H}^H\} \\ &= E\{(H - W \tilde{H}) \tilde{H}^H\} \\ &= E\{H \tilde{H}^H\} - W E\{\tilde{H} \tilde{H}^H\} \\ &= R_{H\tilde{H}} - W R_{\tilde{H}\tilde{H}} = 0 \end{aligned} \quad (4.6)$$

Where, R_{AB} denotes the cross-correlation matrix for matrices A and B of order $N * N$ (i.e., $R_{AB} = E\{AB^H\}$), and $\tilde{H}$ is the LS estimate of the channel given as

$$\tilde{H} = X^{-1} Y = H + X^{-1} Z$$

. The solution for equation (4.6) gives

$$W = R_{H\tilde{H}} R_{\tilde{H}\tilde{H}}^{-1} \quad (4.7)$$

The autocorrelation matrix $R_{\tilde{H}\tilde{H}}$ is given as

$$\begin{aligned} R_{\tilde{H}\tilde{H}} &= E\{\tilde{H} \tilde{H}^H\} \\ &= E\{X^{-1} Y (X^{-1} Y)^H\} \\ &= E\{(H + X^{-1} Z)(H + X^{-1} Z)^H\} \\ &= E\{H H^H\} + E\{X^{-1} Z Z^H (X^{-1})^H\} \\ &= E\{H H^H\} + \frac{\sigma_z^2}{\sigma_x^2} I \end{aligned} \quad (4.8)$$

From equation (4.8), the MMSE estimate of channel is given as

$$\begin{aligned}\hat{H} &= W\tilde{H} = R_{H\tilde{H}}R_{\tilde{H}\tilde{H}}^{-1}\tilde{H} \\ &= R_{H\tilde{H}}(R_{HH} + \frac{\sigma_z^2}{\sigma_x^2}I)^{-1}\tilde{H}\end{aligned}\quad (4.9)$$

$R_{H\tilde{H}}$ denotes the cross-correlation matrix of true channel and estimated channel in frequency domain.

4.5.3 Interpolation Techniques In COMB-Type Pilot Arrangement

In this type of pilot arrangement, channel estimation is done by applying efficient interpolation techniques. Channel information at pilot sub-carriers are used to estimate channels at data sub-carriers through interpolation. Using linear interpolation channel estimated at data-carrier k , $mL < k < (m+1)L$, is given by:

$$\begin{aligned}H_e(k) &= H_e(mL + l) \quad 0 \leq l < L \\ &= (H_p(m+1) - H_p(m))\frac{l}{L} + H_p(m)\end{aligned}\quad (4.10)$$

The performance of second order interpolation is better than the linear interpolation. The estimate of channel using second order interpolation is given by:

$$\begin{aligned}H_e(k) &= H_e(mL + l) \\ &= c_1H_p(m-1) + c_0H_p(m) + c_{-1}H_p(m+1)\end{aligned}\quad (4.11)$$

where,

$$\begin{cases} c_1 = \frac{\alpha(\alpha-1)}{2} \\ c_0 = -(\alpha-1)(\alpha+1), \alpha = \frac{l}{L} \\ c_{-1} = \frac{\alpha(\alpha+1)}{2} \end{cases}$$

To attain higher accuracy for the estimation, we can use higher order interpolation, but the computational complexity increases proportionally with the order of interpolation. Hence, a trade-off has to be maintained between complexity and accuracy.

Chapter 5

Alamouti Coded OFDM

5.1 Introduction to Space-Time code

Fig.5.1 shows a MISO (Multiple Input Single Output) type of channel system, where we have L transmit antennas and one receive antenna [1]. In a cellular system having multiple transmit antenna at the base station is much cheaper than at the mobile station. The L transmit antennas present at the transmitter provide a diversity order of L . The diversity gain is achieved by transmitting same symbol over different antenna at different time instants, i.e, when one antenna is transmitting the other antenna remains silent. But this scheme of transmission wastes the available degree of freedom.

5.2 Alamouti Scheme

Alamouti scheme is a class of STBC. It is the simplest and most elegant scheme for achieving transmit diversity by utilizing the degree of freedom. This scheme uses two transmit antennas and one receive antenna. It achieves the same diversity order as MRRC (Maximal-Ratio Receiver Combining) with one transmit antenna and two receive antennas [13]. Table 5.1 represents the Alamouti System. This scheme can be generalised to two transmit antenna and M receive antennas [14].

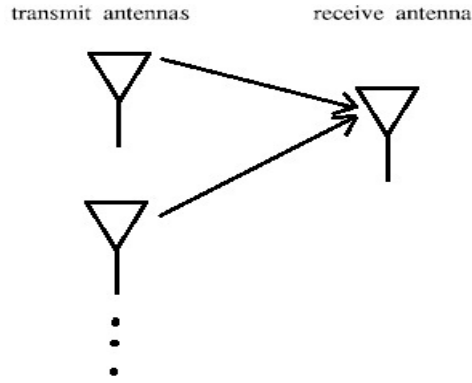


Figure 5.1: MISO System

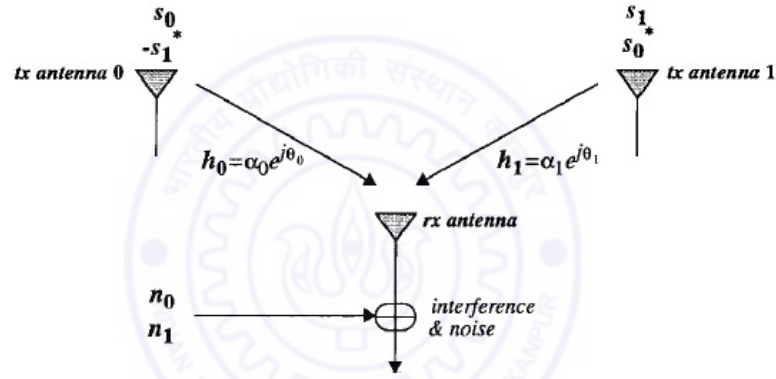


Figure 5.2: Alamouti Scheme

5.2.1 The Encoding and Transmission Scheme

In this scheme two symbols are transmitted simultaneously, from the two antennas. During the first symbol period antenna zero transmits signal s_0 and antenna one transmits s_1 . In the next symbol period antenna zero transmits $-s_1^*$ and antenna one transmits signal s_0^* . Where, $*$ represents the complex conjugate. The transmission scheme is also shown in table 5.1 [13]. The channel modelled for antenna zero is h_0 and the channel modelled for antenna 1 is h_1 . The channel is assumed to remain constant for two symbol duration across the two antennas. If T is considered as symbol duration then the received signal y_0 and y_1 at time t and $t + T$ is given by [13]:

$$y_0 = y(t) = h_0 s_0 + h_1 s_1 + w_0 \quad (5.1)$$

	antenna 0	antenna 1
time t	s_0	s_1
time t+T	$-s_1^*$	s_0^*

Table 5.1: Encoding and Transmission Scheme

$$y_1 = y(t + T) = -h_0 s_1^* + h_1 s_0^* + w_1 \quad (5.2)$$

The above equation (5.1) can be written in vector form as :

$$\begin{bmatrix} y_0 & y_1 \end{bmatrix} = \begin{bmatrix} h_0 & h_1 \end{bmatrix} \begin{bmatrix} s_0 & -s_1^* \\ s_1 & s_0^* \end{bmatrix} + \begin{bmatrix} w_0 & w_1 \end{bmatrix} \quad (5.3)$$

Since, we are interested in detecting s_0 and s_1 . So, the above equation can be rewritten as:

$$\begin{bmatrix} y_0 \\ y_1^* \end{bmatrix} = \begin{bmatrix} h_0 & h_1 \\ h_1^* & -h_0^* \end{bmatrix} \begin{bmatrix} s_0 \\ s_1 \end{bmatrix} + \begin{bmatrix} w_0 \\ w_1^* \end{bmatrix} \quad (5.4)$$

The square matrix of above equation has it's columns orthogonal. Hence, the detection problem for s_0 and s_1 decomposes to two separate scalar problems [1]. The signals are detected at the receiver by combining as follows:

$$\tilde{s}_0 = h_0^* y_0 + h_1 y_1^* \quad (5.5)$$

$$\tilde{s}_1 = h_1^* y_0 - h_0 y_1^* \quad (5.6)$$

The above detection problem can be written in vector form as :

$$\begin{bmatrix} \tilde{s}_0 \\ \tilde{s}_1 \end{bmatrix} = \begin{bmatrix} h_0^* & h_1 \\ h_1^* & -h_0 \end{bmatrix} \begin{bmatrix} y_0 \\ y_1^* \end{bmatrix} = \begin{bmatrix} h_0^* & h_1 \\ h_1^* & -h_0 \end{bmatrix} \begin{bmatrix} h_0 & h_1 \\ h_1^* & -h_0^* \end{bmatrix} \begin{bmatrix} s_0 \\ s_1 \end{bmatrix} + \begin{bmatrix} h_0^* & h_1 \\ h_1^* & -h_0 \end{bmatrix} \begin{bmatrix} w_0 \\ w_1^* \end{bmatrix} \quad (5.7)$$

Hence, the detected symbols can be written as:

$$\tilde{s}_0 = ||h||^2 s_0 + h_0^* w_0 + h_1 w_1^* \quad (5.8)$$

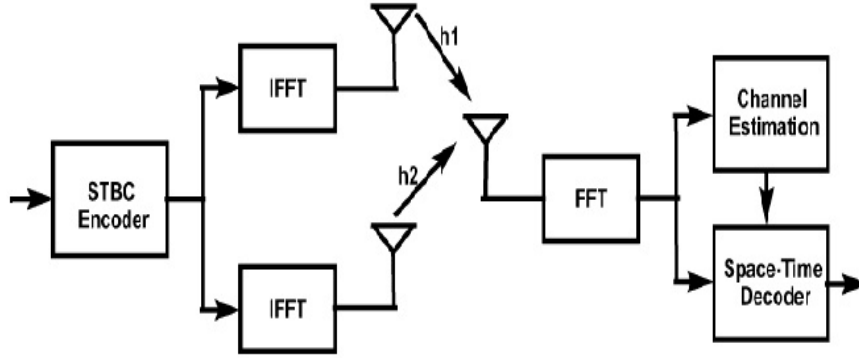


Figure 5.3: Alamouti Coded OFDM system

$$\tilde{s}_1 = ||h||^2 s_1 - h_0 w_1^* + h_1^* w_0 \quad (5.9)$$

Where, $||h||^2$ represents the norm vector of the channel matrix given by $|h_1|^2 + |h_2|^2$

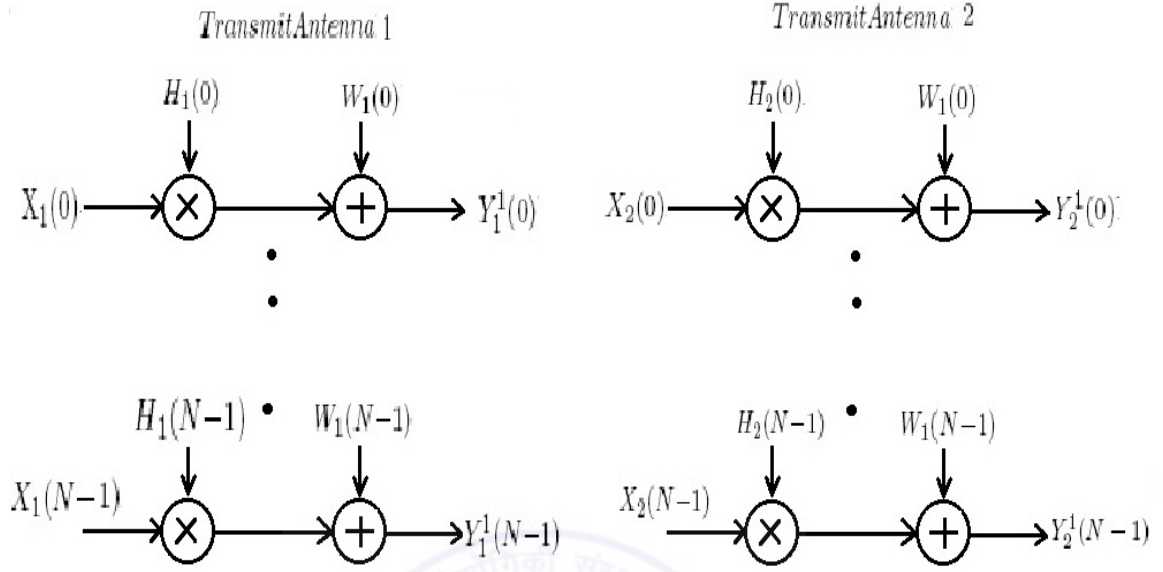
5.3 Alamouti Coded OFDM System

In this system the Alamouti transmission scheme is applied along with the OFDM system. Fig.5.3 shows the system of OFDM along with the Alamouti transmission scheme [15]. The underlying concept of transmission is same as in Alamouti system without OFDM. As shown in fig.5.3, the data is multiplexed into two streams s_0 and s_1 which is then applied to the IFFT block to get the symbols in time domain and then transmitted using the two transmitters. The channel is assumed to remain constant for two symbol periods, so that the OFDM symbols at second symbol period passes through the same channel, which is a reasonable assumption and also makes the system analysis simpler. At the receiver end the symbols are processed by the FFT block and then the symbols are decoded by the space-time decoder.

5.3.1 Frequency Domain Analysis of Alamouti Coded OFDM

Fig.5.4 analyzes the frequency domain analysis for Alamouti coded OFDM. The symbol s_0 is given by

$$s_0 = X_1(k) = [X_1(0), X_1(1), \dots, X_1(N-1)]$$

Figure 5.4: Frequency Domain Analysis at time t

and s_1 is given by

$$s_1 = X_2(k) = [X_2(0), X_2(1), \dots, X_2(N-1)]$$

Let, Y_1^1 and Y_1^2 represents the output of first antenna at time t and time $t+T$. Similarly, Y_2^1 and Y_2^2 represents the output of second antenna at time t and time $t+T$. Since, the channel is assumed to be constant for two time symbols. So, the channel at time t and $t+T$ is the same for antenna 0 as well as for antenna 1. The output from the two antennas at time t can be written as:

$$Y_1^1(k) = H_1(k)X_1(k) + W_1(k) ; k = 0, 1, \dots, N-1 \quad (5.10)$$

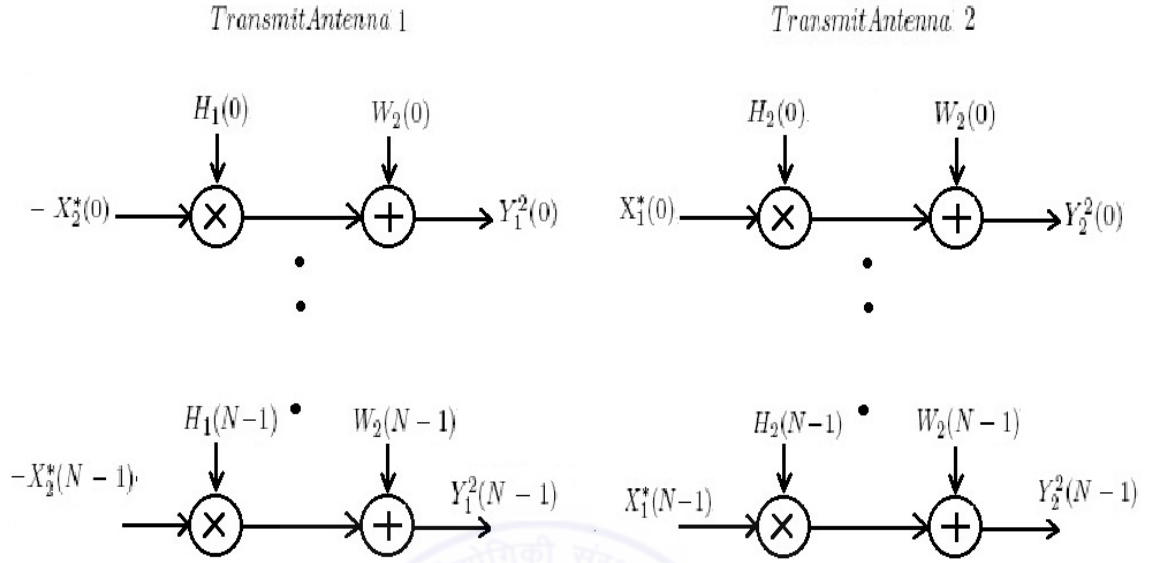
$$Y_2^1(k) = H_2(k)X_2(k) + W_1(k) ; k = 0, 1, \dots, N-1 \quad (5.11)$$

Similarly, the symbols transmitted at time $t+T$ by the two antennas is shown in fig.5.5. The symbol transmitted by antenna 1 is given by

$$s_3 = -X_2^* = [-X_2^*(0), -X_2^*(1), \dots, -X_2^*(N-1)]$$

and that transmitted by antenna 2 is

$$s_4 = X_1^* = [X_1^*(0), X_1^*(1), \dots, X_1^*(N-1)]$$

Figure 5.5: Frequency Domain Analysis at time $t + T$

The output of the two antennas at time instant $t + T$ can be written as:

$$Y_1^2(k) = -H_1(k)X_2^*(k) + W_2(k) \quad ; k = 0, 1, \dots, N-1 \quad (5.12)$$

$$Y_2^2(k) = H_2(k)X_1^*(k) + W_2(k) \quad ; k = 0, 1, \dots, N-1 \quad (5.13)$$

Hence, the received symbols Y_1 and Y_2 is given by the sum of the two transmitted symbols by the two antennas at time t and $t + T$

$$Y_1(k) = H_1(k)X_1(k) + H_2(k)X_2(k) + W_1(k) \quad ; k = 0, 1, \dots, N-1 \quad (5.14)$$

$$Y_2(k) = -H_1(k)X_2^*(k) + H_2(k)X_1^*(k) + W_2(k) \quad ; k = 0, 1, \dots, N-1 \quad (5.15)$$

For decoding purpose we take the conjugate of equation (5.15) to get

$$Y_2^*(k) = -H_1^*(k)X_2(k) + H_2^*(k)X_1(k) + W_2^*(k) \quad ; k = 0, 1, \dots, N-1 \quad (5.16)$$

Where, $Y_1(k)$ is the received symbol at time t and $Y_2(k)$ is the received symbol at time $t + T$. Equation (5.14) and (5.16) can be combined and can be written in condensed form as

$$Y(k) = A(k)X(k) + W(k) \quad ; k = 0, 1, \dots, N-1 \quad (5.17)$$

Where,

$$Y(k) = \begin{bmatrix} Y_1(k) \\ Y_2^*(k) \end{bmatrix}, \quad A(k) = \begin{bmatrix} H_1(k) & H_2(k) \\ H_2^*(k) & -H_1^*(k) \end{bmatrix}, \quad X(k) = \begin{bmatrix} X_1(k) \\ X_2(k) \end{bmatrix}, \quad W(k) = \begin{bmatrix} W_1(k) \\ W_2^*(k) \end{bmatrix}$$

The symbols at the receiver can be detected by multiplying equation (5.14) with $A^H(k)$ and can be represented as

$$\begin{aligned} \hat{X}(k) &= A^H(k)Y(k) \\ &= A^H(k)A(k)X(k) + A^H(k)W(k) \\ &= \|H(k)\|^2 X(k) + W'(k); \quad k = 0, 1, \dots, N-1 \end{aligned} \quad (5.18)$$

Where,

$$\hat{X}(k) = \begin{bmatrix} \hat{X}_1(k) \\ \hat{X}_2(k) \end{bmatrix}, \quad A^H(k) = \begin{bmatrix} H_1^*(k) & H_2(k) \\ H_2^*(k) & -H_1(k) \end{bmatrix}, \quad \|H(k)\|^2 = |H_1(k)|^2 + |H_2(k)|^2$$

and

$$W' = A^H(k)W(k)$$

Chapter 6

Simulations And Results

The plot for *BER* (Bit Error Rate) vs E_b/N_o in dB for BPSK and 16-QAM are simulated and compared with the theoretical probability of error. The probability of error for BPSK in AWGN and Rayleigh fading channel are:

$$p = \frac{1}{2} * \operatorname{erfc}\left(\sqrt{2 * \frac{E_b}{N_o}}\right) \text{ (AWGN)} \quad (6.1)$$

$$p_e = \frac{1}{2} * \left(1 - \sqrt{\frac{E_b/N_o}{1 + E_b/N_o}}\right) \text{ (Rayleigh)} \quad (6.2)$$

$$P_b = p_e^2 * (1 + 2 * (1 - p_e)) \text{ (STBC)} \quad (6.3)$$

Where, erfc denotes the complementary error function.

Below equation gives the lower bound BER for 16-QAM in Rayleigh fading channel [16]:

$$P_e = \frac{1}{2} - \frac{3}{8} * \sqrt{\frac{1}{1 + \frac{2.5}{E_b/N_o}}} - \frac{1}{4} * \sqrt{\frac{1}{1 + \frac{5/18}{E_b/N_o}}} + \frac{1}{8} * \sqrt{\frac{1}{1 + \frac{0.1}{E_b/N_o}}} \text{ (Lower bound Rayleigh)} \quad (6.4)$$

$$P_b = p_e^2 * (1 + 2 * (1 - p_e)) \text{ (STBC)} \quad (6.5)$$

Above equations are used to plot the theoretical *BER* for BPSK and 16-QAM at different E_b/N_o .

Table 6.1 represents the parameters considered for simulation of the different schemes discussed in previous chapters for BPSK and 16-QAM.

Modulation Mode	BPSK	16QAM
Number of Bits per Symbol	1	4
FFT Points	64	128
Number of Sub-carriers	64	128
Length of CP	16	16
Number of Data Sub-carriers	52	112
Channel Model	AWGN and Rayleigh	AWGN and Rayleigh
Channel Taps	10	10

Table 6.1: Simulation Parameters

In Table 6.1 we have described the parameters that have been used for the simulation of the different schemes for BPSK and 16-QAM system. The channel is modelled as AWGN and Rayleigh. First, we have shown the results for BPSK system and later the results of 16-QAM.

Fig.6.1 shows the plot for theoretical BER for BPSK in AWGN and Rayleigh fading channel at different E_b/N_o . The simulation plot for BPSK OFDM in Rayleigh fading channel coincide with the theoretical BER plot of the equation 6.2. The simulation has been performed for E_b/N_o over the range of 0 to 25 dB. The simulation has been performed assuming perfect channel information. The performance in presence of Rayleigh fading is poorer compared to that in AWGN channel because of the fading nature of channel.

Fig.6.2 shows the plot for uniform frequency hopping OFDM in Rayleigh fading channel at different E_b/N_o . The performance for simulated uniform hopping coincides with the theoretical BER plot of the equation 6.2. Hence, the hopping technique can provide the advantage of low interception probability without any performance degradation. The hopping technique also exploits the available degree of freedom.

Fig.6.3 shows the plot for non-uniform frequency hopping OFDM in Rayleigh fading channel at different E_b/N_o . The plot for simulated non-uniform hopping coincides with the theoretical BER plot of the equation 6.2. Hence, this hopping technique can also provide the same advantage as that of uniform hopping to obtain much lower interception probability without any performance degradation.

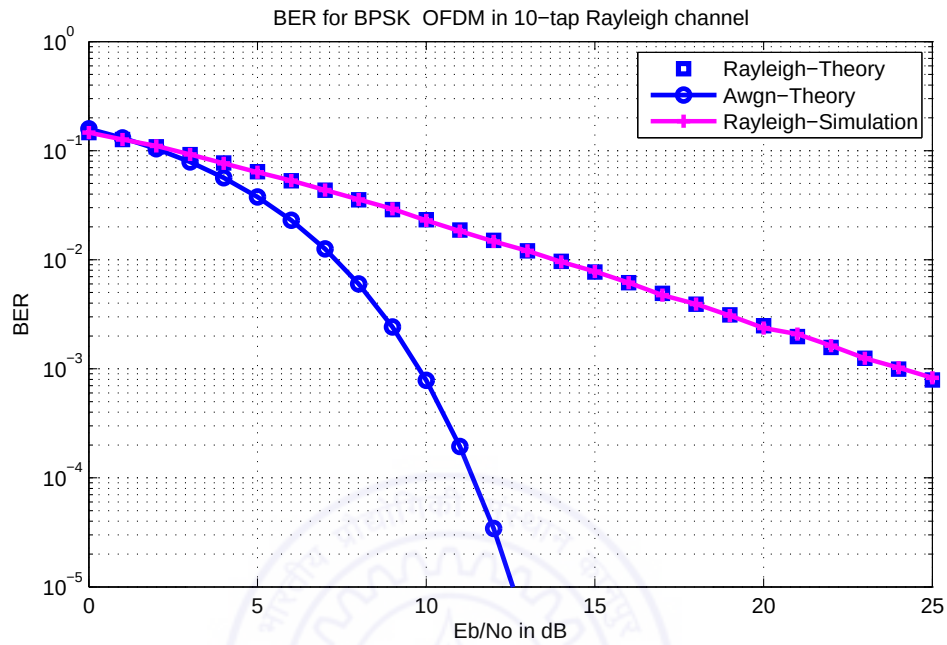


Figure 6.1: Plot for BPSK OFDM in Rayleigh fading channel

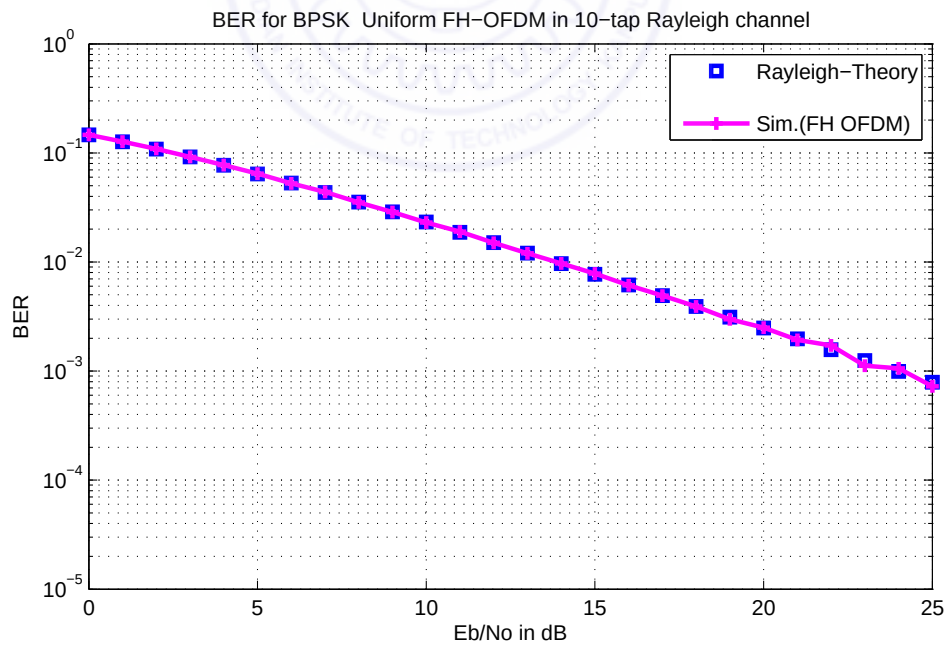


Figure 6.2: Plot for Uniform Frequency Hopping BPSK OFDM in Rayleigh fading channel

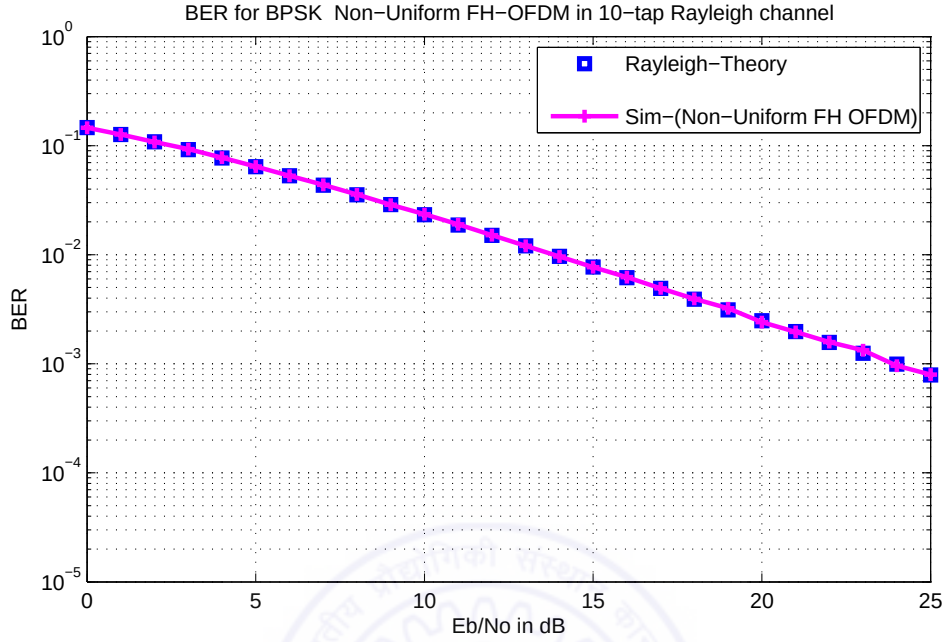


Figure 6.3: Plot for Non-Uniform Frequency Hopping BPSK OFDM in Rayleigh fading channel

Fig.6.4 shows the plot for BPSK Alamouti coded STBC in Rayleigh fading channel at different E_b/N_o . The plot for simulated BPSK Alamouti coded STBC coincides with the theoretical BER plot of the equation 6.3 for Alamouti coded STBC. As can be seen from the figure, the performance of simulated STBC is better than that of the theoretical BER plot of the equation 6.2 because of the diversity gain achieved due to the transmit diversity. For the range of E_b/N_o from 0 to 25 dB the achieved gain is around 0 to 15 dB.

Fig.6.5 shows the plot for BPSK Alamouti coded OFDM STBC in Rayleigh fading channel at a different E_b/N_o . The plot for simulated BPSK Alamouti coded OFDM STBC coincides with the theoretical BER plot of the equation 6.3. As can be seen from the figure, the performance of simulated STBC is better than that of the theoretical BER plot of the equation 6.2 by 0 to 15 dB because of the diversity gain achieved due to the transmit diversity. Hence, the STBC OFDM achieves higher data rate without any performance degradation.

Fig.6.6 shows the plot for BPSK AFH OFDM in Rayleigh fading channel at different E_b/N_o . The plot for simulated AFH OFDM shows better performance as compared to that

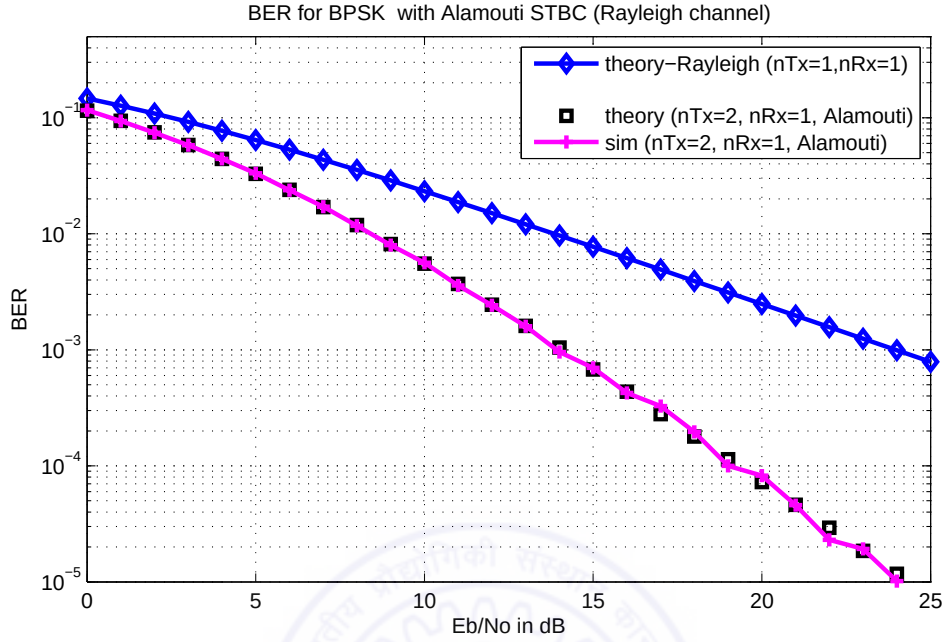


Figure 6.4: Plot for BPSK Alamouti in Rayleigh fading channel

of theoretical BER plot of the equation 6.2. AFH OFDM outperforms the OFDM system by 0 to 5 dB at the same BER within 0 to 25 dB E_b/N_o range. The gain is achieved due to the adaptive hopping applied for the system.

Fig.6.7 shows the plot for AFH Alamouti coded OFDM in Rayleigh fading channel at different E_b/N_o . The plot for simulated AFH Alamouti coded OFDM outperforms the theoretical BER plot of the equation 6.2 by 0 to 12 dB within the E_b/N_o range of 0 to 25 dB and also outperforms the theoretical BER plot of the equation 6.3 for STBC OFDM by 0 to 5 dB within the E_b/N_o range of 0 to 25 dB. The gain achieved is due to the adaptive hopping applied for the system.

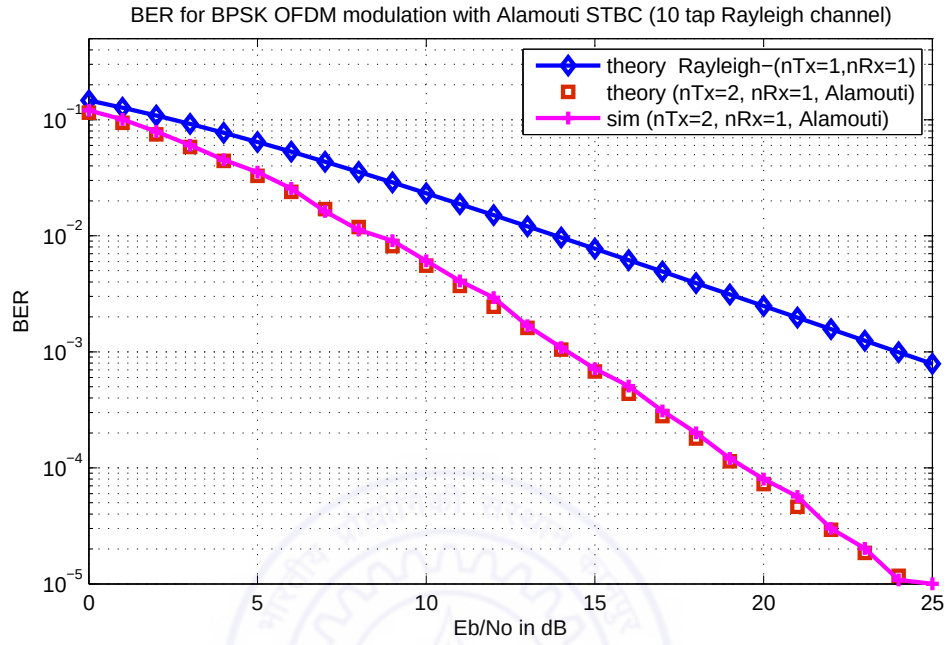


Figure 6.5: Plot for Alamouti Coded BPSK OFDM in Rayleigh fading channel

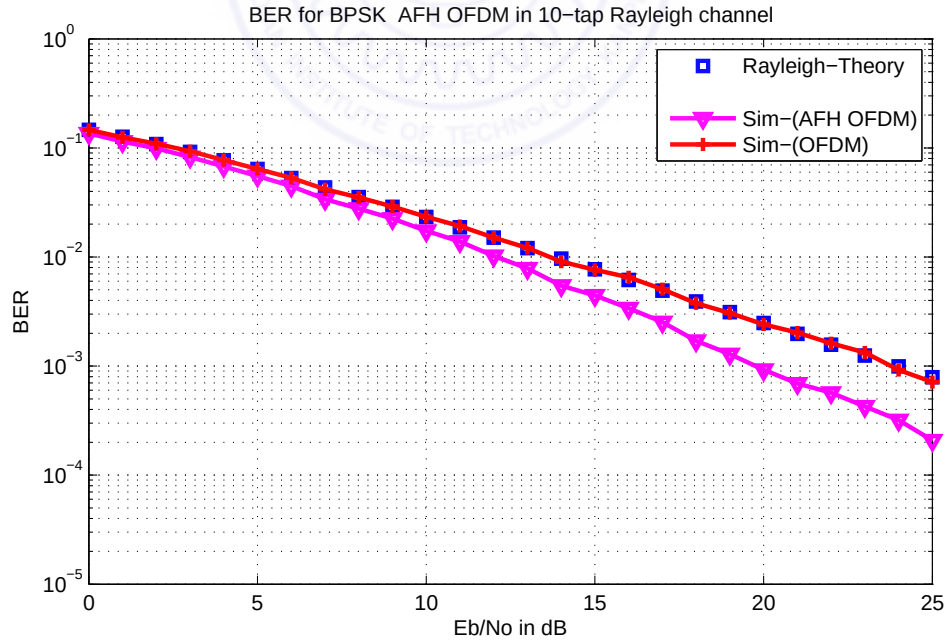


Figure 6.6: Plot for Adaptive Frequency Hopping BPSK OFDM in Rayleigh fading channel

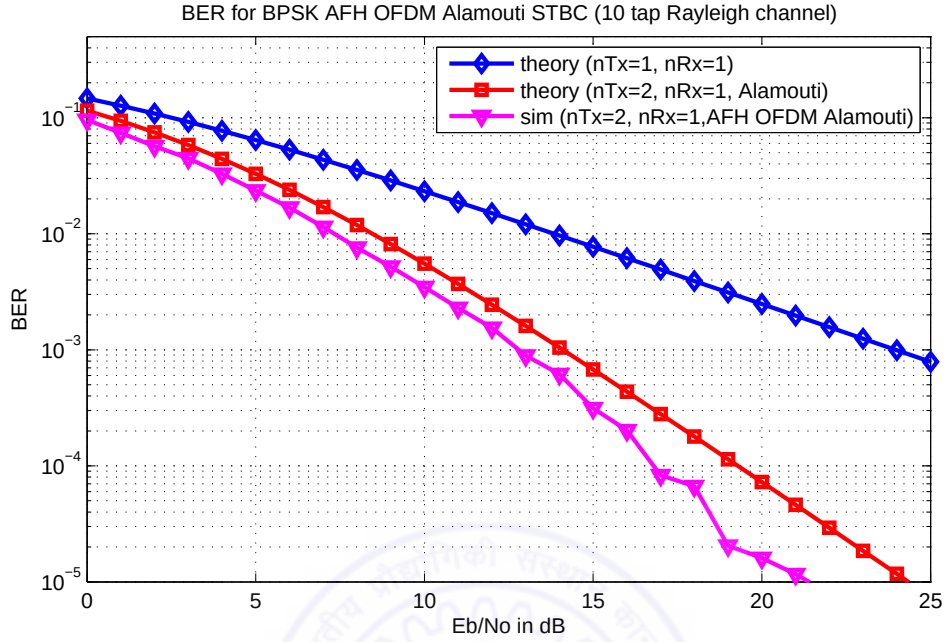


Figure 6.7: Plot for AFH BPSK Alamouti Coded OFDM in Rayleigh fading channel

Fig.6.8 to fig.6.11 has been simulated for the same system model with 16-QAM as it was modelled for BPSK. The simulation has been performed assuming perfect channel information.

Fig.6.8 shows the plot for theoretical lower bound for BER of 16-QAM in Rayleigh fading channel at different E_b/N_o . The simulated plot validates the performance of OFDM as the simulated plot is above the theoretical lower bound for BER plot for the equation 6.4. The simulation for E_b/N_o has been performed for the range of 0 to 25 dB.

Fig.6.9 shows the plot for uniform frequency hopping OFDM at different E_b/N_o in Rayleigh fading channel. The performance of simulated uniform hopping OFDM and that of simulated OFDM coincide with each other and also the plot is above the theoretical lower bound of the BER plot of the equation 6.4. Hence, the uniform hopping technique provides low probability of interception without any performance degradation.

Fig.6.10 shows the plot for non-uniform frequency hopping OFDM at different E_b/N_o in Rayleigh fading channel. The performance of simulated non-uniform hopping OFDM and that of simulated OFDM coincide with each other and also the plot is above the theoretical

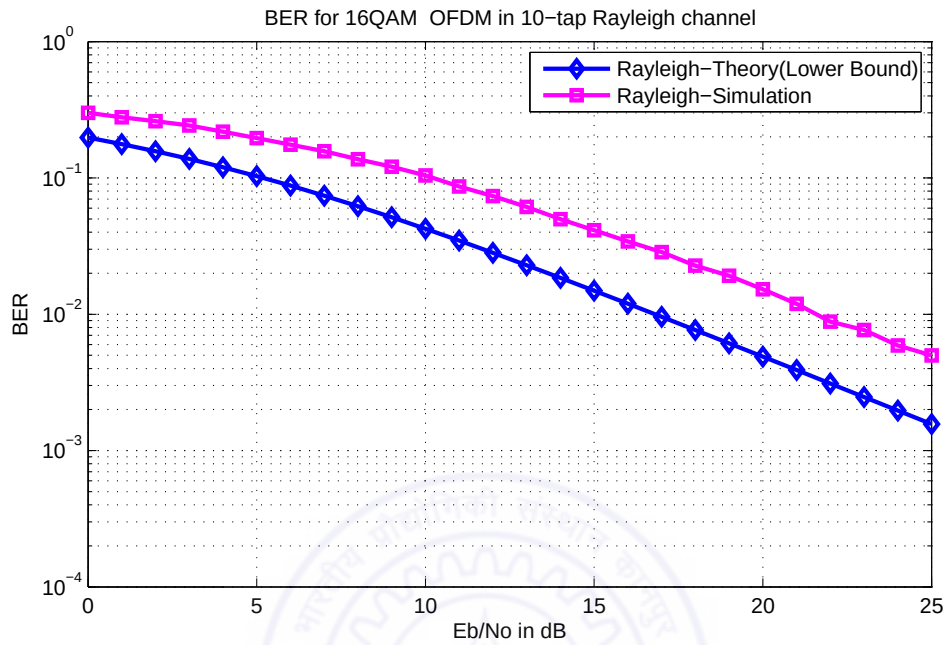


Figure 6.8: Plot for 16-QAM OFDM in Rayleigh fading channel

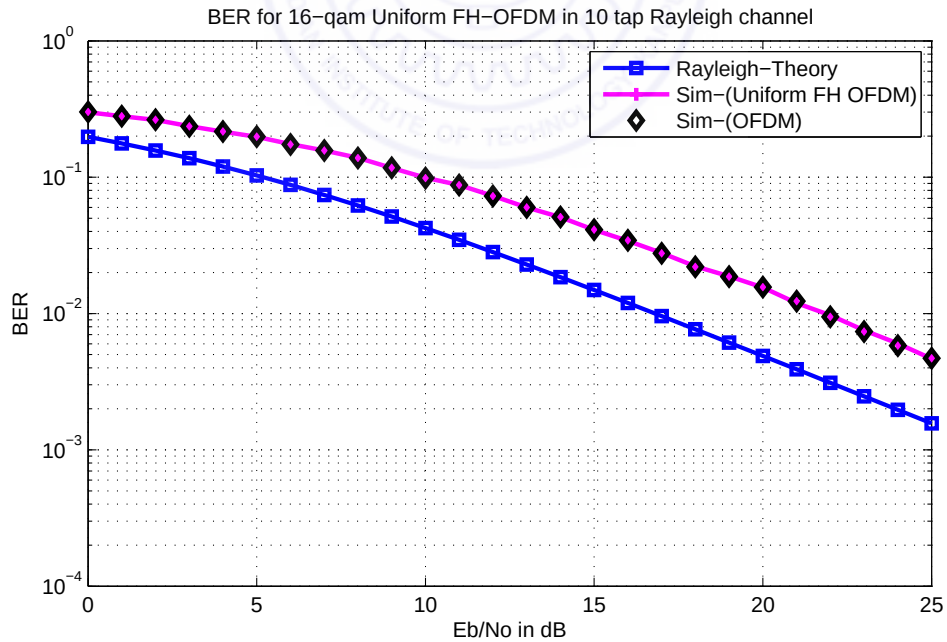


Figure 6.9: Plot for Uniform Frequency Hopping 16-QAM OFDM in Rayleigh fading channel

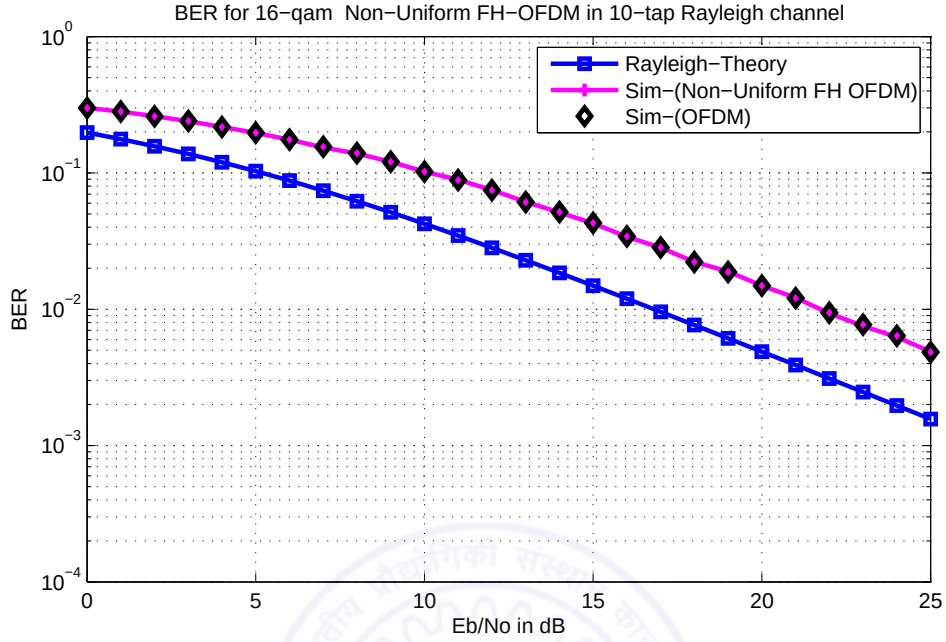


Figure 6.10: Plot for Non-Uniform Frequency Hopping 16-QAM OFDM in Rayleigh fading channel

lower bound.

Fig.6.11 shows the plot for least square block estimated 16-QAM OFDM in Rayleigh fading channel at different E_b/N_o . The simulated plot for OFDM and that of LS estimated OFDM validates the simulation. The simulation has been performed assuming perfect channel knowledge as well as estimating the channel using least square estimation. The performance of LS estimated 16-QAM OFDM is poor by 0 to 3 dB within 0 to 25 dB E_b/N_o range as compared to that of CSI (Channel State Information) 16-QAM OFDM because of the channel estimation.

Fig.6.12 shows the plot for Alamouti coded STBC OFDM at different E_b/N_o in Rayleigh fading channel. The simulation has been performed assuming perfect channel information. The performance of Alamouti coded STBC OFDM and that of theoretical Alamouti coded STBC OFDM is same as the plot of both coincide with each other. Hence, this system provides high data rate transmission with same performance and also achieves high gain as compared to that of 16-QAM OFDM.

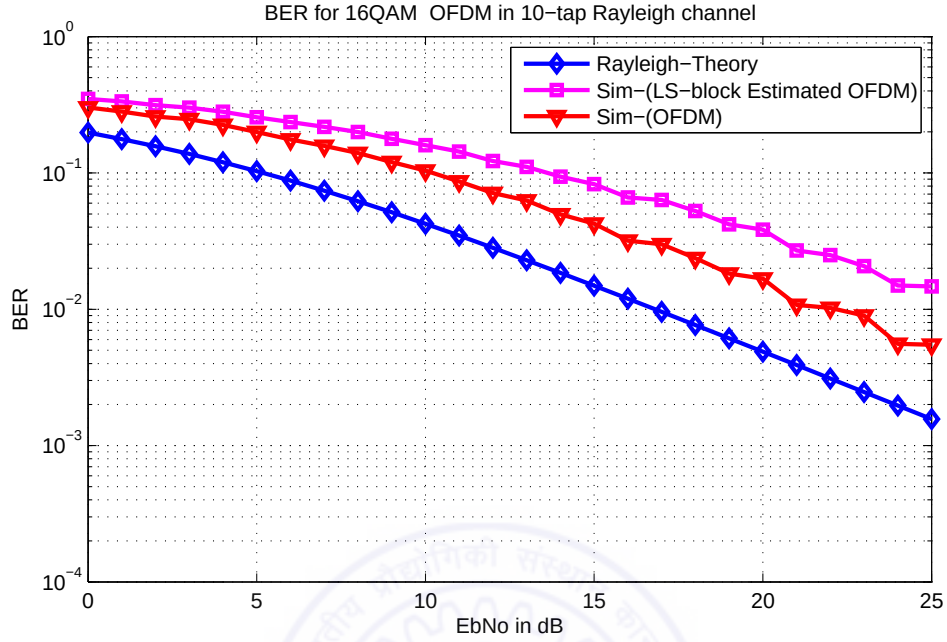


Figure 6.11: Plot for LS Block Estimated 16-QAM OFDM in Rayleigh fading channel

Fig.6.13 shows the plot for AFH OFDM in Rayleigh fading channel at different E_b/N_o . The plot for simulated AFH OFDM shows that it outperforms the simulated OFDM by 0 to 5 dB within 0 to 30 dB E_b/N_o range. Hence, the AFH system enhance the performance, as can be seen from fig.6.13. The gain in performance comes from adaptive hopping of the data based on channel condition.

Fig.6.14 shows the plot for AFH Alamouti coded STBC OFDM in Rayleigh fading channel at different E_b/N_o . The plot for simulated AFH Alamouti coded STBC OFDM shows that it outperforms the theoretical lower bound for BER of 16-QAM in the equation 6.4 by 2 to 18 dB and also outperforms the theoretical Alamouti coded STBC OFDM of the equation 6.5 by 0 to 4 dB at the same BER within 0 to 25 dB E_b/N_o range. The gain in performance comes from adaptive hopping of the data based on channel condition.

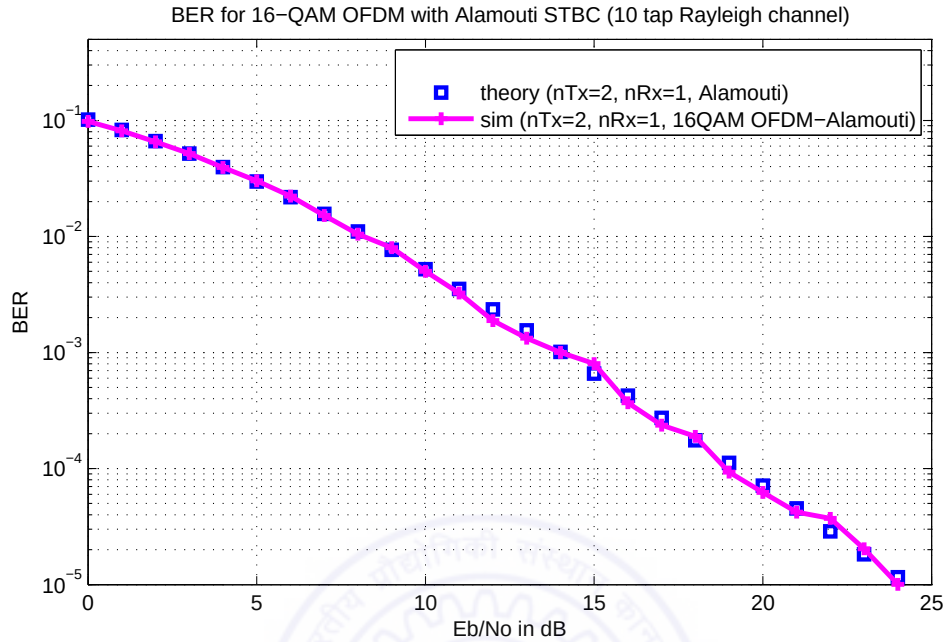


Figure 6.12: Plot for Alamouti coded STBC 16-QAM OFDM in Rayleigh fading channel

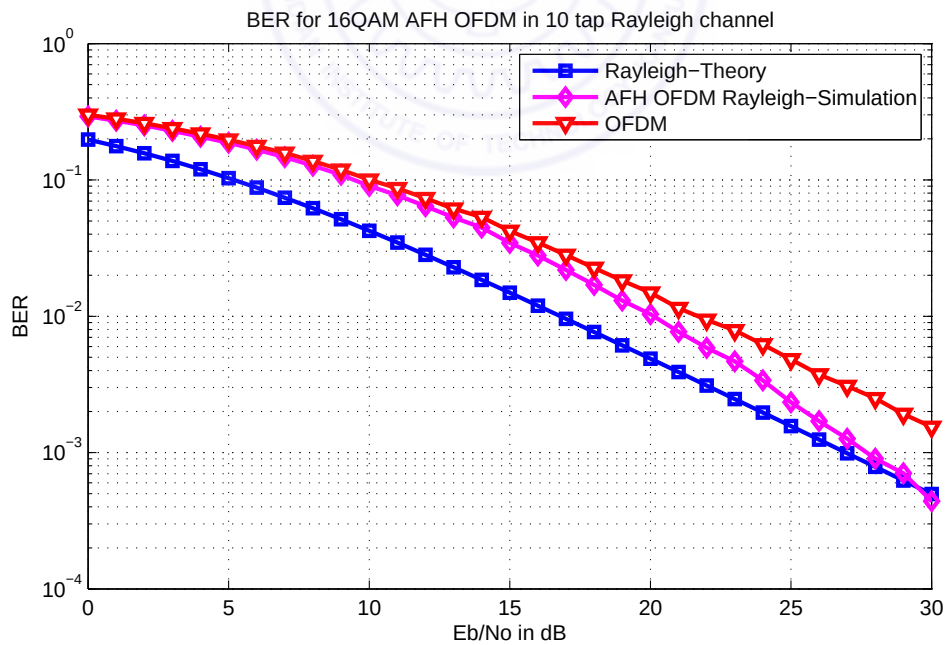


Figure 6.13: Plot for Adaptive Frequency Hopping 16-QAM OFDM in Rayleigh fading channel

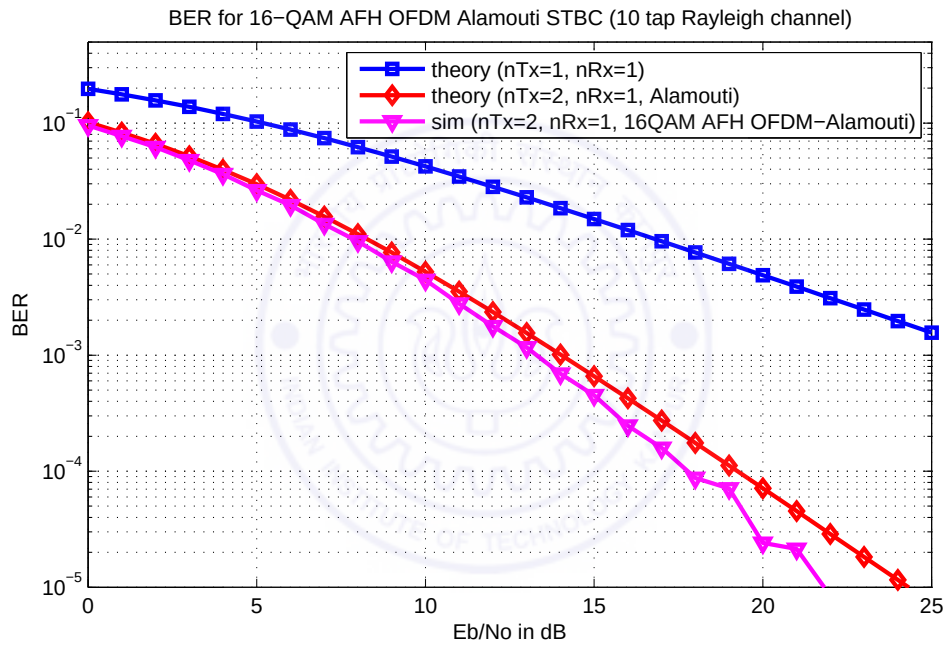


Figure 6.14: Plot for AFH 16-QAM Alamouti-Coded STBC OFDM in Rayleigh fading channel

Chapter 7

Conclusions And Future Work

7.1 Conclusions

We have analyzed the performance of AFH Alamouti coded OFDM system with the AFH OFDM and OFDM systems for BPSK. We found that the performance of AFH Alamouti coded OFDM over Alamouti coded OFDM improves by 0 to 5 dB while the performance of AFH OFDM over OFDM also improves by 0 to 5 dB. Since, the Alamouti code provides diversity gain which improves the system of AFH Alamouti coded OFDM as compared to that of OFDM by 0 to 12 dB.

We also have analyzed the performance of AFH Alamouti coded OFDM system with the AFH OFDM and OFDM systems for 16-QAM. We found that the performance of AFH Alamouti coded OFDM over Alamouti coded OFDM improves by 0 to 5 dB while the performance of AFH OFDM over OFDM also improves by 0 to 5 dB. Since, the Alamouti code provides diversity gain which improves the system of AFH Alamouti coded OFDM as compared to that of OFDM by 0 to 8 dB.

Hence, we conclude that the system proposed using AFH Alamouti-coded OFDM improves the performance of the existing OFDM techniques.

7.2 Future Work

Some of the future prospects of the adaptive frequency hopped Alamouti-coded OFDM system are:

- 1) It can be applied to MIMO systems to achieve higher diversity order and better performance.
- 2) This system can be used in multi-user scenario.



Appendix A

Algorithm

A.1 Algorithm For Adaptive Frequency Hopping in OFDM

It is assumed that the channel remains constant for l OFDM symbol period, Where, l can vary from 4 to 10. It is also assumed that there exist a feedback mechanism through which the receiver communicates the channel condition back to the transmitter (in real communication scenario, a separate feedback channel is used to pass on information like power, channel conditions, etc.) Since, the receiver knows the channel conditions, then it also knows the hopping pattern adopted by the transmitter, which helps the receiver to de-hop the signals back at the receiver before de-mapping.

Algorithm 1 Adaptive Hopping based on Channel State Information

1. OFDM symbol block of length N is decomposed into smaller blocks (m sub-blocks of l data bits such that $m * l = N$, where N is total number of sub-carriers).
 2. First data of each sub-block is zero padded.
 3. SNR of channel corresponding to each data of the sub-block is calculated.
 4. For each sub-block taken one at a time,
 5. Find $\min.\{snr\}$ across that sub-block.
 6. **if** $pos.(\min.\{snr\}) \neq 1$ **then**
 7. Swap the data of the corresponding $\min.\{snr\}$ position with the zero padded first data.
 8. Continue the above iteration till the last sub-block.
 9. **end if**
 10. Append all the sub-blocks chronically to form the OFDM symbol.
 11. Transmit the adaptively hopped symbol after ofdm modulation.
-

Algorithm 2 Adaptive Hopping based on Channel estimation

1. OFDM symbol block of length N is decomposed into smaller blocks (m sub-blocks of l data bits such that $m * l = N$, where N is total number of sub-carriers).
 2. First data of each sub-block is zero padded.
 3. **if** $\text{mod}(L, l) = 0$ **then**
 4. Where L is the symbol number and l is the period for pilot transmission.
 5. OFDM symbol of pilot block is transmitted, which helps in estimating the channels.
 6. Channel conditions is assumed to remain constant for l symbol period.
 7. SNR of channel corresponding to each data of the sub-block is calculated.
 8. For each sub-block taken one at a time,
 9. Find $\min.\{snr\}$ across that sub-block.
 10. **if** $\text{pos}(\min.\{snr\}) \neq 1$ **then**
 11. Swap the data of the corresponding $\min.\{snr\}$ position with the zero padded first data.
 12. Continue the above iteration till the last sub-block.
 13. **end if**
 14. **end if**
 15. Append all the sub-blocks chronically to form the OFDM symbol.
 16. Transmit the adaptively hopped symbol after ofdm modulation.
-

Algorithm 3 Adaptive Hopping for Alamouti-coded OFDM

1. Two OFDM symbol are taken s_1 and s_2 that are to be transmitted by two antennas.
 2. Both OFDM symbol block of length N is decomposed into smaller blocks (m sub-blocks of l data bits such that $m * l = N$, where N is total number of sub-carriers).
 3. First data of each sub-block is zero padded.
 4. For each sub-block taken one at a time,
 5. Find $\min.\{snr\}$ across that sub-block.
 6. **if** $\text{pos.}(\min.\{snr\}) \neq 1$ **then**
 7. Swap the data of the corresponding $\min.\{snr\}$ position with the zero padded first data.
 8. Continue the above iteration till the last sub-block to get the modified S_1 and S_2 .
 9. **end if**
 10. Append all the sub-blocks chronically to form the OFDM symbol.
 11. Transmit the adaptively hopped symbol after ofdm modulation.
 12. S_3 and S_4 are the second OFDM period symbols from the two transmit antenna.
 13. $S_3 = -S_2^*$ and $S_4 = S_1^*$.
-

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